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Analysis of the Energetic Feature of the Loaded Gait with Variation of the Trunk Flexion Angle

Ji-il Park, Hyungtae Seo, Jihyuk Park, Kwang jin Choi, Kyung-Soo Kim, Soohyun Kim

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Abstract**—**The purpose of the research is to investigate the energetic feature of the backpack load on soldier's gait with variation of the trunk flexion angle. It is believed that the trunk flexion variation of the loaded gait may cause a significant difference in the energy cost which is often in practice in daily life. To this end, seven healthy Korea military personnel participated in the experiment and are tested under three different walking postures comprised of the small, natural and large trunk flexion. There are around 5 degree differences of waist angle between each trunk flexion. The ground reaction forces were collected from the force plates and motion kinematic data are measured by the motion capture system. Based on these data, the impulses, momentums and mechanical works done on the center of body mass (COM) during the double support phase were computed. The result shows that the push-off and heel strike impulse are not relevant to the trunk flexion change, however the mechanical work by the push-off and heel strike were changed by the trunk flexion variation. It is because the vertical velocity of the COM during the double support phase is increased significantly with an increase in the trunk flexion. Therefore, we can know that the gait efficiency of the loaded gait depends on the trunk flexion angle. Also, even though the gravitational impulse and pre-collision momentum are changed by the trunk flexion variation, the after-collision momentum is almost constant regardless of the trunk flexion variation.

Keywords**—**Loaded gait, collision, impulse, gravity, heel strike, push-off, gait analysis.

I. INTRODUCTION

MOBILITY is the number-one priority of the military operations. Troops with high mobility are able to move more quickly and place the enemy in a disadvantage position more effectively. From the historical perspective, units with high mobility have got the victory in the war. Thus, the mobility of the dismounted foot soldier has considered the important determinant of the success of military operations. Here, the indispensable factor for the improvement of the mobility is the military load carriage. On this account, considerable research of the soldier's gait has investigated currently for reducing the stress of loads around the military committees and organizations.

Jeffrey M. Schiffman demonstrated that an increase in load weight and a change in rucksack weight position change both the individual's postural sway and the structure of the sway [1].

Stewart A Birrell examined the effects of progressive increments in carried load on GRF parameters and suggested that both vertical and anteroposterior GRF parameters increase proportionally when load is added in 8 kg increments from 0kg to 40kg. It is apparent that adding weight to the body will increase the overall vertical ground reaction forces [2].

Albert A. Adams III found that the use of extremity armor on soldiers resulted in a metabolic cost increase as the mass of the armor increased and did affect gait kinematics. Metabolic cost normalized to the body mass increased significantly when extremity armor was worn. Range of motion (ROM) of the ankle decreased in walking with extremity armor, while hip and knee ROMs increased with the use of extremity armor [3].

Joseph Knapik analyzed the historical, physiological, biomechanical, and medical aspects of load carriage synthetically. However, after all, they suggested that making loads lighter, improving load distribution, using appropriate physical training, selecting proper equipment, and choosing specific techniques directed at injury prevention will all facilitate load carriage [4].

Marcelo Castro analyzed the influence of different speeds on the GRFs, impulses and mean vertical force during the gait of people submitted to occasional overload [5].

However, the previous studies have not evaluated the energetic feature of the trunk flexion change of the loaded gait. To this end, for three case of the trunk flexion, the impulses, momentums, and mechanical works on the COM during the double support phase are analyzed by the experimental data.

II. METHODS

A. Subjects

To investigate the energetic feature of the loaded gait, total seven subjects who were the trained military personnel participated in the gait experiments. They have worked more than three years of the military service and also skilled with carrying the military backpacks. The mean age was 29.4 ±2.7 years, height 175.03 ±3.71cm, and weight 75.1 ±7.94kg. Prior to participation in the experiment, subjects completed a health survey questionnaire and were informed about the experimental procedure verbally and in writing. Consent form approved by KAIST IRB was obtained from all participants.

B. Experimental Procedure

All participants carried a 25kg military backpack and walked on a 12 meter walkway. Backpack used in gait experiment was actual military backpack of Korea army and the size of it is width 36cm × length 18cm × height 52cm. Subjects walked

Ji-il Park and Kwang jin Choi are with the Department of after action review, Korea Combat Training Center, Inje, South Korea(e-mail:tinz64@kaist.ac.kr, kjin49@gmail.com).

Hyungtae Seo, Jihyuk Park, and Soohyun Kim are with the Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, South Korea (e-mail: htseo@kaist.ac.kr,jihpark@kaist.ac.kr, soohyun@kaist.ac.kr).

Kyung-Soo Kim is with the Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, South Korea (phone: +82-42-350-3047; fax: +82-42-350-5201; e-mail: kyungsookim@ kaist.ac.kr).

with their own gait frequency under three different trunk flexion : natural (-16.43 ± 2.59), small (-9.86 ± 4.08), and large flexion (-23.59 ± 3.79). Here, the natural trunk flexion implies physically comfortable posture posed by the trained soldiers. Large and small trunk flexion means bending at the waist forward and extending the upper body backward, respectively. Every trial was repeated several times until subjects stepped on the force plates exactly. However, every participant has own gait posture, trunk flexion angle at the pre and after-collision were measured differently for each trial. Finally, there are 63 observations (i.e. 7 subjects × 3 walking postures × 3 trials) in the data set.

C. Experimental Procedure

Ground reaction forces of three consecutive steps and motion capture data were measured by three force platforms and otion capture cameras at a 200Hz sampling frequency. The data was filtered using Butterworth 5th order low-pass filter with cutoff frequency of 20Hz for force plate data and 20Hz for motion capture data. Total 13 reflective markers were attached on subject's body: two on each shoulder, three on each pelvic and sacral, two on each knee, two on each ankle, two on each heel, and two on each metatarsal.

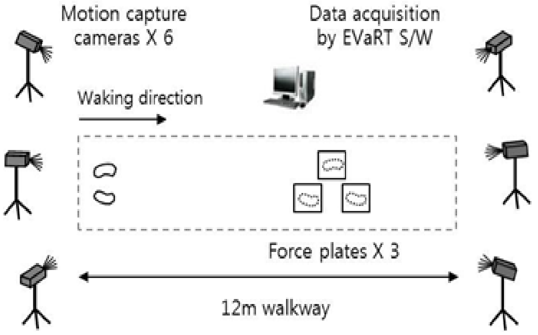

Fig. 1 Experimental setup: Experiment setup was composed with three force plates (AccuGait, AMTI, MA, US) mounted on walkway, six motion capture cameras (Hawk, Motion Analysis, CA, US) around walkway, and EVaRT software for data acquisition

III. Data Analysis

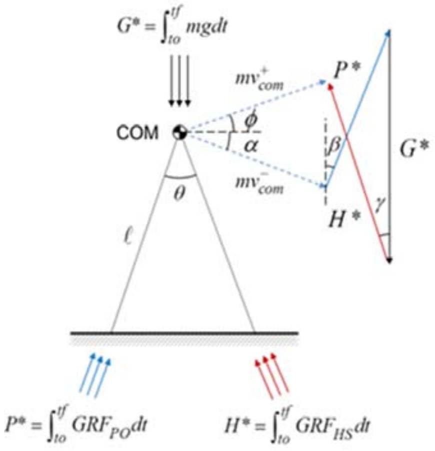

Fig. 2 Impulse-momentum diagram of the step to step transition. The momentum of the COM moved upward due to the push-off, heel strike, and gravitational impulses during the double support phase (the step-to-step transition process). Parameters are as follows: direction of the after-collision momentum (ϕ), direction of the pre-collision momentum (α), direction of the push-off impulse (β), direction of the heel strike impulse (γ), leg length (ℓ), and inter-leg angle (θ)

Magnitudes of the push-off and heel strike impulses were calculated by integrating GRFs and magnitude of the gravitational impulse was calculated by mgΔt. Directions of the collision impulses were derived from the direction of average GRFs in the sagittal plane during the double support. Here, t_0 is the time of the pre-collision and t_f is the time of the after-collision. The COM velocity was computed by integrating the acceleration data extracted from the GRFs and the momentum of COM was computed by the scalar product of the body mass and the COM velocity.

$$\begin{cases} \int \frac{GRF_x}{m} dt = \int \ddot{x} dt = v_x \\ \int \frac{GRF_y - mg}{m} dt = \int \ddot{y} dt = v_y \end{cases} \tag{1}$$

The mechanical works on the COM during the double support phase were calculated by the GRFs and COM velocity. The mechanical work done by the push-off (W_{push}) was computed by integration of the dot product of the GRFs of the trailing leg and the COM velocity. The mechanical work done by the heel strike (W_{heel}) was computed by integration of the dot product of the GRFs of the leading leg and the COM velocity. Also, the mechanical work done by gravity ($W_{gravity}$) was derived from integration of the scalar product of the body weight and the COM velocity. The mechanical work by the hip torque (W_{ss}) was computed by the integration of the dot product of the GRFs and the COM velocity during the single support phase.

$$\begin{cases} w_{push} = \int_{to}^{tf} \vec{F}_{trail} \cdot \vec{v}_{com} dt = \int_{to}^{tf} (F_{trail(x)} \cdot v_{x(com)} + F_{trail(y)} \cdot v_{y(com)}) dt \\ w_{heel} = \int_{to}^{tf} \vec{F}_{lead} \cdot \vec{v}_{com} dt = \int_{to}^{tf} (F_{lead(x)} \cdot v_{x(com)} + F_{lead(y)} \cdot v_{y(com)}) dt \\ w_{gravity} = \int_{to}^{tf} mg \cdot \vec{v}_{com} dt \\ w_{ss} = \int_{to}^{tf} \vec{F}_{swing} \cdot \vec{v}_{com} dt = \int_{to}^{tf} (\vec{F}_x \cdot \vec{v}_{x(com)} + \vec{F}_y \cdot \vec{v}_{y(com)}) dt \end{cases} \tag{2}$$

Regression analysis of data was conducted to confirm the significant difference subjected to the trunk flexion change. The standard level of significance was statistically considered p<.05.

IV. RESULTS

As the trunk flexion angle became larger, the duration of the double support phase was slightly reduced ((p<0.05); Fig. 3 (A)). The gravitational impulse was also decreased significantly as the trunk flexion increased (p<0.05) since the gravitational impulse (mgΔt) is dependent on the double support phase time (Δt). Whereas, the push-off and heel strike impulses were not changed subjected to the trunk flexion angle contrary to expectation in practice (p>0.05; Fig. 3 (A)). It is also apparent that the ground reaction forces were slightly increased depending on the trunk flexion increase. Similar to the magnitude cases, the directions of the impulses were not changed by the trunk flexion variation (p>0.05; Fig. 3 (C)). The direction of the pre-collision momentum is closely correlated with the trunk flexion change. The angle of the pre-collision momentum (α) significantly increased with the trunk flexion change ((p<0.05; Fig. 3 (D)), while the direction of the after-collision momentum (ϕ) was almost constant regardless of the trunk flexion change (p>0.05; Fig. 3 (D)). It is because the angle difference of the pre-collision momentum (α) was offset through the step-to-step transition process (The gravitational impulse was reduced with the increase in the trunk flexion). Also, it can be observed that the direction of pre and after-collision momentums the natural trunk flexion is almost up-down symmetric (Fig. 3 (D)).

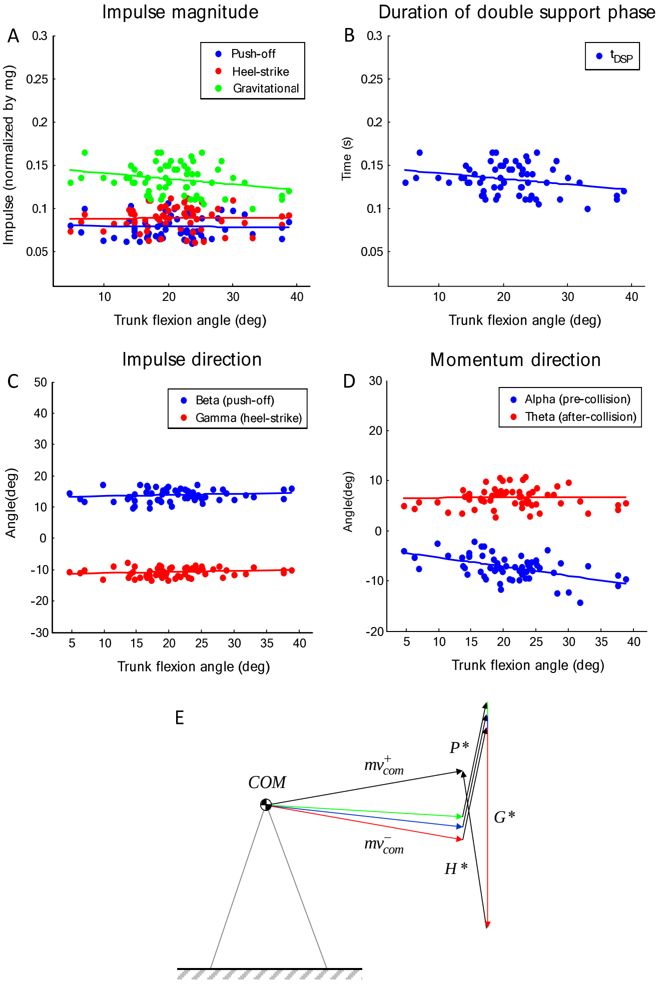

Fig. 3 Empirical data of the loaded gait as a function of the trunk flexion angle. (A) Magnitudes of the push-off, heel strike, and gravitational impulses. Each impulse was normalized by the subject's body weight (mg). Blue, red, and green circle are the push-off impulse (P*), heel strike impulse (H*), and gravitational impulse (G*), respectively. (B) Time duration of the double support phase (Δt). (C) Directions of the push-off and heel strike impulses. Blue, and red circles are the angle of the push-off impulse (β) and heel strike impulse (γ). (D) Direction of the pre and after-collision momentums. Blue and red circles are the angle of the after-collision momentum ( ) and pre-collision momentum. (α) Solid lines are the regression line. (E) Impulse-momentum diagram composed of the empirical data. Green, blue, and red solid lines are the small, natural, and large trunk flexion. As the trunk flexion angle change, the direction of pre-collision momentum ( ) and gravitational impulse (G*) are changed, however the after-collision momentum was not changed with regard to the trunk flexion change. Noticeable change of the COM momentum was only the direction of the pre-collision momentum. The direction of the pre-collision momentum moved downward as the trunk flexion angle increased

TABLE I
Empirical Data and Regressions as a Function of Trunk Flexion Angle

	Mean	Regression	R^2	P-value
P*	0.0788	y =-0.00006x+0.0801	0.0157	0.8101(>0.05)
G*	0.0884	y=00004x+0.0876	0.0163	0.8814 (>0.05)
H*	·	y=-0.0006x+0.1468	0.0681	0.0405 (<0.05)
Alpha	·	y=-0.1816x-3.5202	0.2615	0.0000216 (<0.05)
Beta	13.8732°	y=0.0385x+13.071	0.0197	0.2761 (>0.05)
Gamma	10.7027°	y=-0.031x+11.349	0.0227	0.2426 (>0.05)
Theta	6.8281°	y=0.0026x+6.5639	0.0166	0.9429 (>0.05)

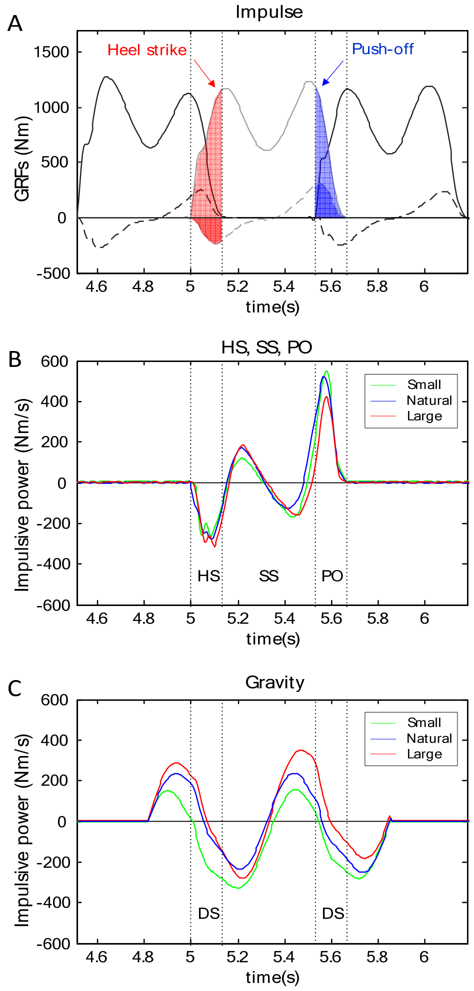

Fig. 4 Impulsive power during the double support phase. As the trunk flexion increased, the impulsive power by the heel strike was also increased, whereas the impulsive power by the push-off was decreased. It is because the vertical velocity of the COM at the pre-collision was increased by bending at the waist. Whereas, the forward velocity did not affect the mechanical works since the forward velocity was not relevant to the trunk flexion change (A) The vertical (solid lines) and anteroposterior (dotted lines) GRFs through three consecutive steps (R→L→R). Red and blue shaded areas indicate the heel strike and push-off impulses, respectively (B) Impulsive powers of the heel strike (HS), single support phase (SS) and push-off (PO) Green, blue, and red lines are the small, natural, and large trunk flexion, respectively (C) Impulsive powers of the gravity subjected to the trunk flexion change. Sectional areas (DS) indicate the mechanical works by the gravitational impulse

Mechanical works done on the COM during the double support phase were calculated by the time integral of the impulsive power (Fig. 5), which were obtained by the dot product of the external forces and COM velocity. Mechanical work done by the push-off impulse was positive and showed decreasing trend as bend at the waist, whereas the mechanical work done by the heel strike impulse was negative and showed increasing trend significantly as the trunk flexion became larger (Figs. 4 (B), (C), and 5). Here, each sectional area (HS, SS, PO, and Gravity) in Figs. 4 (B), (C) indicate the mechanical works by the push-off, heel strike, hip torque and gravity, respectively. It is interesting to note that the mechanical work by the gravity changed from negative to positive definite as bend at the waist. It implies the mechanical work by the gravity at the small trunk flexion stand in the way of walking forward and the mechanical work by the gravity at the large trunk flexion help to walk forward.

Contrary to the expectation, the mechanical work done by the hip torque during the single support phase was close to zero in any trunk flexion. Interestingly, in the particular case of the natural trunk flexion, the energy lost by the heel strike was compensated by only input energy by the push-off. This finding may support the Kuo's theory that the least costly gait was achieved by providing all input energy with only the mechanical work by the push-off (without the mechanical work by the hip torque) [6].

In case of the small and large trunk flexion, the energy lost by the heel strike was not perfectly compensated by the input energy by the push-off. However, since the total net work during one gait cycle was almost zero, the steady-state gait was maintained regardless of the trunk flexion change. To put it concretely, the energy lost by the heel strike was compensated by the combination of the mechanical works by push-off and gravity. The mechanical works by the gravity compensated for the difference between the mechanical works by the push-off and heel strike. Therefore, it is apparent that the double support phase is the almost important event because the total net works are determined by the step-to-step transition process.

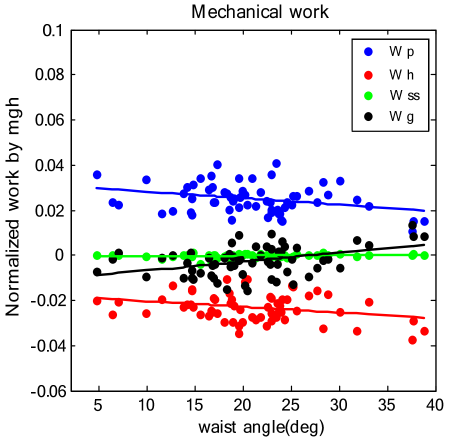

Fig. 5 Mechanical works on the COM as a function of the trunk flexion change. Blue, red, green, and black circles are the mechanical works by the push-off, heel strike, hip torque, and gravity. It was observed that the mechanical works done by the push-off and heel-strike were larger than the other two mechanical works done by the gravity during the double support phase and hip torque on the stance leg during the single support phase

TABLE II
EMPIRICAL DATA AND REGRESSIONS AS A FUNCTION OF TRUNK FLEXION ANGLE

	Regression	R^2	P-value
Work by push-off	y=-0.0003x+0.0315	0.1267	0.0046 (<0.05)
Work by heel strike	y=-0.0003x-0.0178	0.0817	0.0243 (>0.05)
Work by gravity	y=0.0004x-0.0108	0.1732	0.0061 (<0.05)
Work by hip torque	y=-0.00002x+0.0006	0.0463	0.0931(>0.05)

V. DISCUSSION

It is worth nothing that the push-off, heel strike impulses may not necessarily be changed with the trunk flexion change in the loaded gait. It can be estimated that the waist joint hold the upper body's movement, so that the collision impulses were not changed as a function to the trunk flexion change. Therefore, we computed joint torques from the lower segment to the upper segment by inverse dynamics with Newton-Euler equations in order to identify the variation of the joint torques by the trunk flexion change.

As anticipated, the waist joint toque was only relevant to the trunk flexion change (Fig. 6 (A)). The waist joint torque at the large trunk flexion was negative in order to extend upper body backward, whereas the waist joint torque at the small trunk flexion was positive to bend at the upper body forward. However, noticeable variations were not observed in the ankle, knee, and hip joint torques (Figs. 6 (B)-(D)). It can be known that the waist joint torque don't make the shift of the upper body affect the motion of the lower body. Which is why we felt fatigue differently, subjected to the trunk flexion change. For such a reason, the collision impulses were not changed as a function to trunk flexion change.

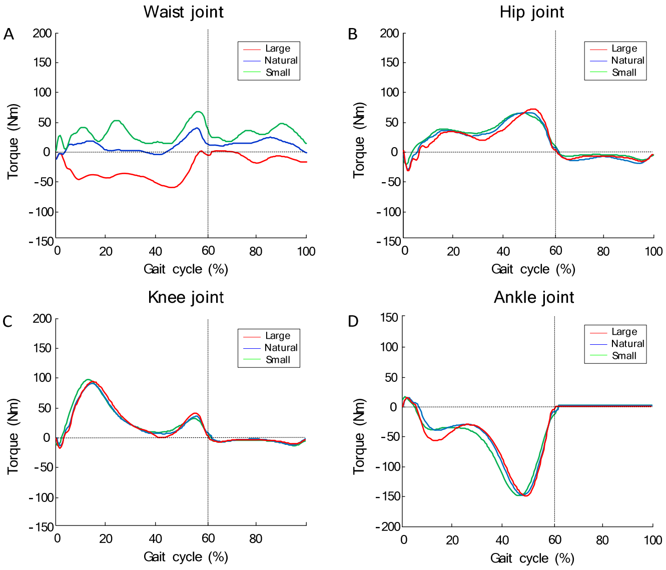

Fig. 6 Joint torques variation subjected to the trunk flexion angle. Joint toques are calculated by kinematic dada from motion capture system and kinetic data from force plates. Green, blue, and red solid lines are small, natural, and large trunk flexion, respectively. (A) Lumbar (waist) joint torque. (B) Hip joint torque (C) Knee joint torque (D) Ankle joint torque

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Ji-il Park was born in Gwangju, South Korea, on June 4, 1982. He received the B.E. degree in Mechanical engineering from the Korea Military Academy in 2005. He also received the M.E. degree in in Foreign Affairs and National Security from Hankuk University of Foreign Studies in 2012 and the M.E. degree in Mechanical engineering from Korea Advanced Institute of Science and Technology in 2013. He is a captain in the Republic of Korea army. His present research is concerned with the optimal walking posture of soldier.