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Analysis of the Loaded Gait Subjected to the Trunk Flexion Change

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***Abstract*—**In the paper, the energetic features of the loaded gait are newly analyzed depending on the trunk flexion change. To investigate the loaded gait, walking experiments are performed for five subjects and, the ground reaction forces and kinematic data are measured. Based on these information, we compute the impulse, momentum and mechanical works done on the center of body mass, through the trunk flexion change. As a result, it is shown that the trunk flexion change does not affect the impulses and momentums during the step-to-step transition as well. However, the direction of the pre-collision momentum does change depending on the trunk flexion change, which is degenerated just after (or during) the collision period.

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

I. INTRODUCTION

WALKING is known to be an indispensable activity in the daily round of life. However, it is difficult to analyze the features, because each person has his own characteristic gait patterns and the human walking is a complicated process actuated by various muscles. Thus, for last a couple of decades, an attention has been paid to understand the generically characteristic gait pattern of human being.

McGeer proposed the passive dynamic walking model powered by only gravity without control and energy input [3]. Garcia proposed a passive working model for simulation, i.e., the so-called simplest working model [4]. This model assumes that (i) two rigid legs are massless, (ii) point-masses at the end of the legs are negligible, and (iii) body mass at the hip is a point-mass. However, these two passive models rely on only the gravity to move forward so that the ankle push-off is not considered. In [5], Kuo suggested the energetics of actively powered locomotion. However, active powered walking model by Kuo also has the defect that the gravity impulse during the step-to-step transition of the human gait is neglected due to the instantaneous collision.

It is known that the step-to-step transition (i.e., double support phase) occupies about 20% of the gait cycle [6], which should not be neglected for the gait analysis. It is because that the step-to-step transition during the double support phase is a crucial event for the periodicity of human gait [9]–[11]. In [7], Kuo also indicated that most of work for human walking occurs during the double support phase. To address this, in [1] and [2], Yeom proposed a novel theoretical model that includes the contribution of the gravity to the momentum change of the center of mass (COM) of the body during the step-to-step transition. In this paper, differently from the normal gait analysis, we investigate the effect of the trunk flexion change on the human gait patterns.

In general, it is believed that the trunk flexion change may cause a significant difference in the energy cost of the loaded gait, which is often in practice in daily life. However, regardless of various models and theories on the human walking, there has little study on the loaded gait subjected to the trunk flexion change.

To this end, for various cases of the trunk flexion change, the push-off impulse, heel strike impulse, pre-collision momentum, after-collision momentum and mechanical works on the COM during the double support phase are analyzed either by the computation based on the finite collision model [1], [2] or by experiments.

In Section II, the framework for analysis adopted in the paper is introduced, and, the actual data is analyzed in Section III. The concluding remarks follows in Section IV.

II. ANALYSIS FRAMEWORK

A. Experimental Data Collection

As shown in Fig. 1, the gait experiment was performed on the force plate (AccuGait, AMTI, MA, US) to measure the ground reaction force (GRF) and the kinematic data from the motion capture cameras (Hawk, Motion Analysis, CA, US).

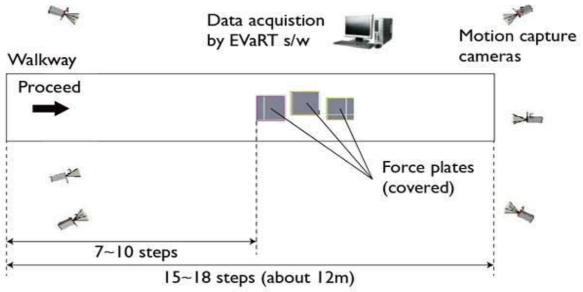

Fig. 1 Experiment setup

TABLE I
TRUNK ANGLE (UNIT: °)

Large flexion	Natural flexion	Small flexion
-23.59 ± 3.79	-16.43 ± 2.59	-9.86 ± 4.08

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Five subjects who are the trained active-duty soldiers participated in the gait experiments. They carried a military back pack of 25kg and walked on a 12 meters walkway under three different conditions of trunk flexion: large, natural and small flexion as listed in Table I. Here, the natural flexion implies the most comfortable posture posed by the test subjects. Nine trials for each subject were collected for three different trunk flexions.

B. Computation of Impulses during the Collision

In [2] (or [1]), it has been known that the impulse-momentum of the COM during the collision (at a step-to-step transition) can be described as shown in Fig. 2. Here, ϕ, α, β, γ, ℓ and θ are directions of the after-collision momentum (mv_{com}^{+}), pre-collision momentum (mv_{com}^{-}), push-off impulse (P*), heel strike impulse (H*), leg length and a half of the inter-leg angle, respectively. Also, G* denotes the gravitational impulse, which is a main idea of the finite collision model.

In general, the impulses can be obtained from the GRF data as illustrated in Fig. 3. By integrating the measured GRF data, one may compute P*, H*, and G*. Also, the direction of the impulses can be obtained by computing the averages of the vertical GRF and anteroposterior GRF during the double support phase.

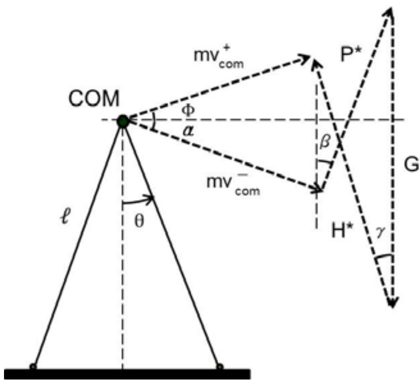

Fig. 2 Impulse-momentum diagram

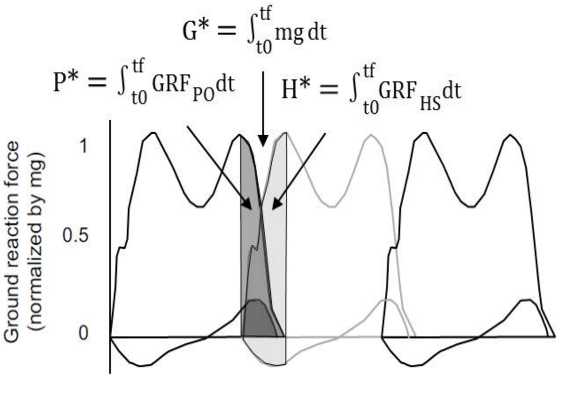

Fig. 3 GRF data through three steps (step sequence: right→left→right) t_0 is the time of pre-collision and t_f is the time of after-collision

C. Computation of Momentums during the Collision

In order to calculate the momentums of the COM during the collision, the data for COM movement such as the velocity and position are necessary. One may utilize the data from the motion capture camera. However, this provides inaccurate information in practice since the accurate location of the COM, where a IR marker is attached, may not be identified exactly. Therefore, we compute the velocity and position of the COM by integrating the acceleration data (extracted from the GRF data) as follows:

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

$$\begin{cases} \int v_x dt = P_x \\ \int v_y dt = P_y \end{cases} \tag{2}$$

Observe the position and velocity of the COM computed from the GRF data in Fig. 4.

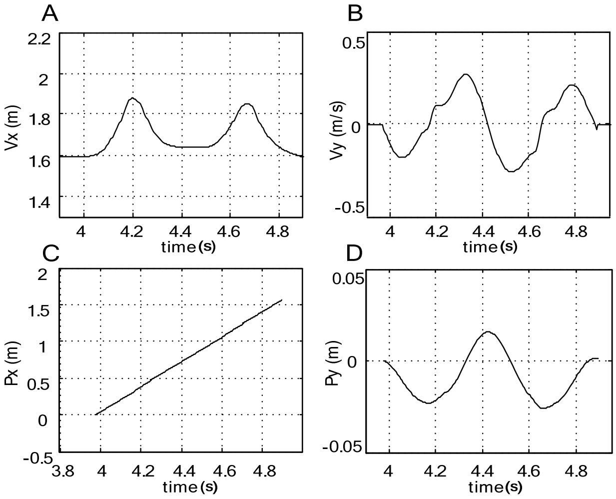

Fig. 4 Velocity and position of the COM. (A) V_x (Forward direction), (B) V_y (Vertical direction), (C) P_x (Forward direction), and (D) P_y (Vertical direction)

D. Mechanical Works on the COM

The mechanical works done on the COM by each impulse (P*, H* and G*) during the double support phase are defined by the push-off impulse (P*) in scalar forms as follows [3]:

$$\begin{cases} W_{push} = \frac{P}{2m}\left\{P + 2mv_{com}^{-}\sin(\beta-\alpha) + H\cos(\beta+\gamma) - G\cos\beta\right\} \\ W_{gravity} = \frac{G}{2m}\left\{G + 2mv_{com}^{-}\sin\alpha - P\cos\beta - H\cos\gamma\right\} \\ W_{heel} = \frac{H}{2m}\left\{H - 2mv_{com}^{-}\sin(\alpha+\gamma) + P\cos(\beta+\gamma) - G\cos\gamma\right\} \end{cases} \tag{3}$$

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In addition, the work done by the hip torque can be expressed as follows [4]. Superscript + and f indicate the initial and final state of the single support phase.

$$w_{hip}=\frac{1}{2}m\left(\left|v_{com}^{f}\right|^{2}-\left|v_{com}^{+}\right|^{2}\right)+mgl\cos(\theta^{f}-\theta^{+}) \qquad (4)$$

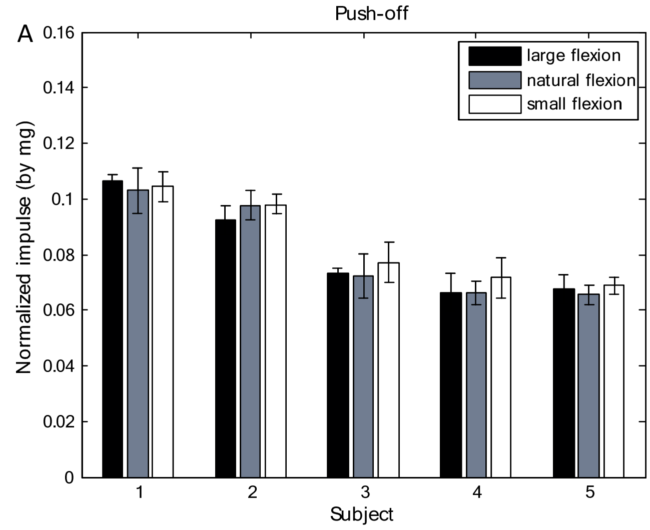
III. ANALYSIS OF THE LOADED GAIT

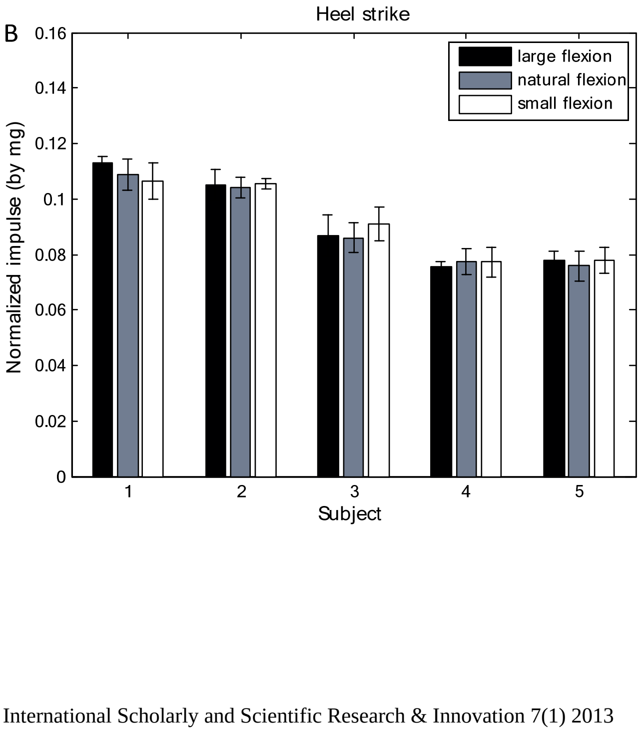
A. Magnitude and Direction of the Impulse

The magnitudes of the push-off, heel-strike and gravitational impulses are normalized by the subject's body weight (*mg*) and plotted in Fig. 5.

Interestingly, it can be observed that the magnitudes of impulses are not relevant to the trunk flexion change. While, the gravitational impulse was changed since the double support phase time was decreased as the trunk flexion.

The directions of the impulses can be derived from the average vector of the GRF data during the double support phase as described in Section II. B. The computed results are shown in Fig. 6. Similar to the magnitude cases, the directions of the impulses are not affected by the trunk flexion change.





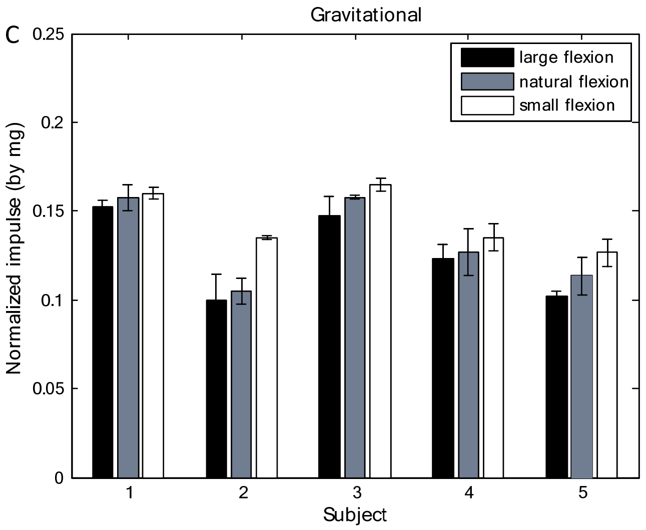


Fig. 5 Impulse magnitudes by the trunk flexion change. (A) Push-off impulse, (B) Heel strike impulse, and (C) Gravitational impulse

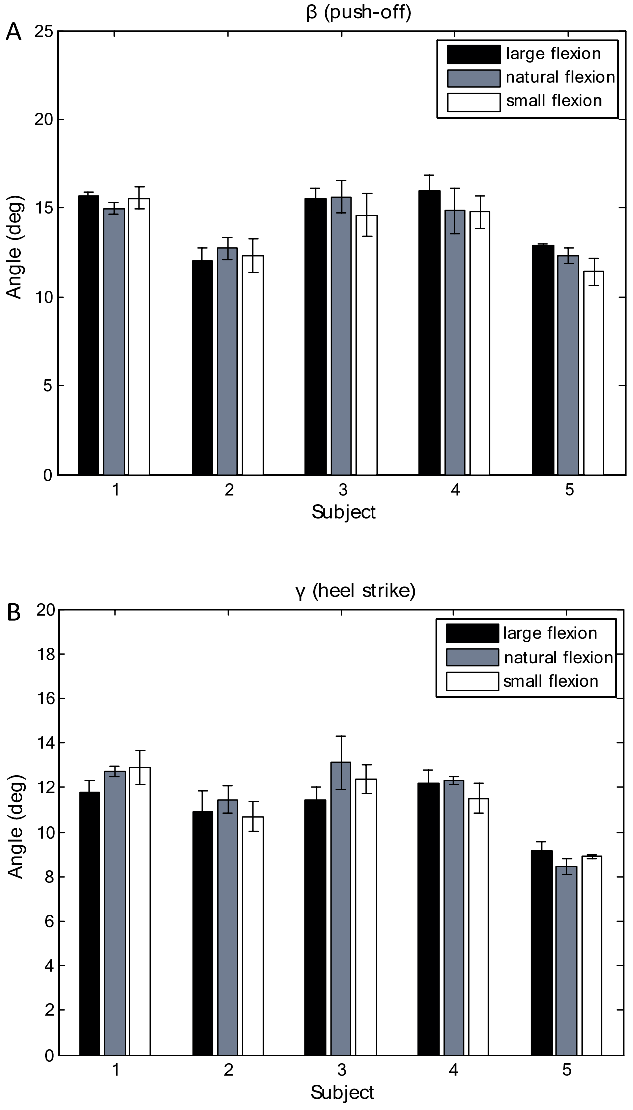


Fig. 6 Impulse directions by the trunk flexion change. (A) Push-off impulse, and (B) Heel strike impulse

B. Direction of the Momentum

The directions of the momentums are shown in Fig.7. It is noted that the trunk flexion change does not affect the direction of after-collision momentum. However, the direction of the pre-collision momentum is significantly affected by the flexion change (see Fig.7(A)).

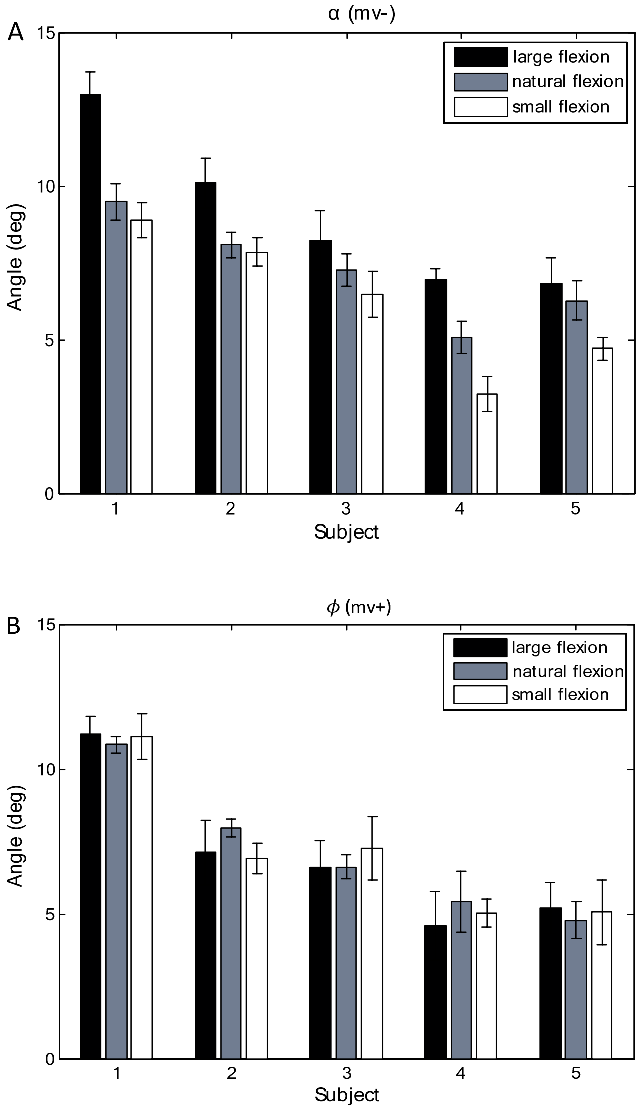
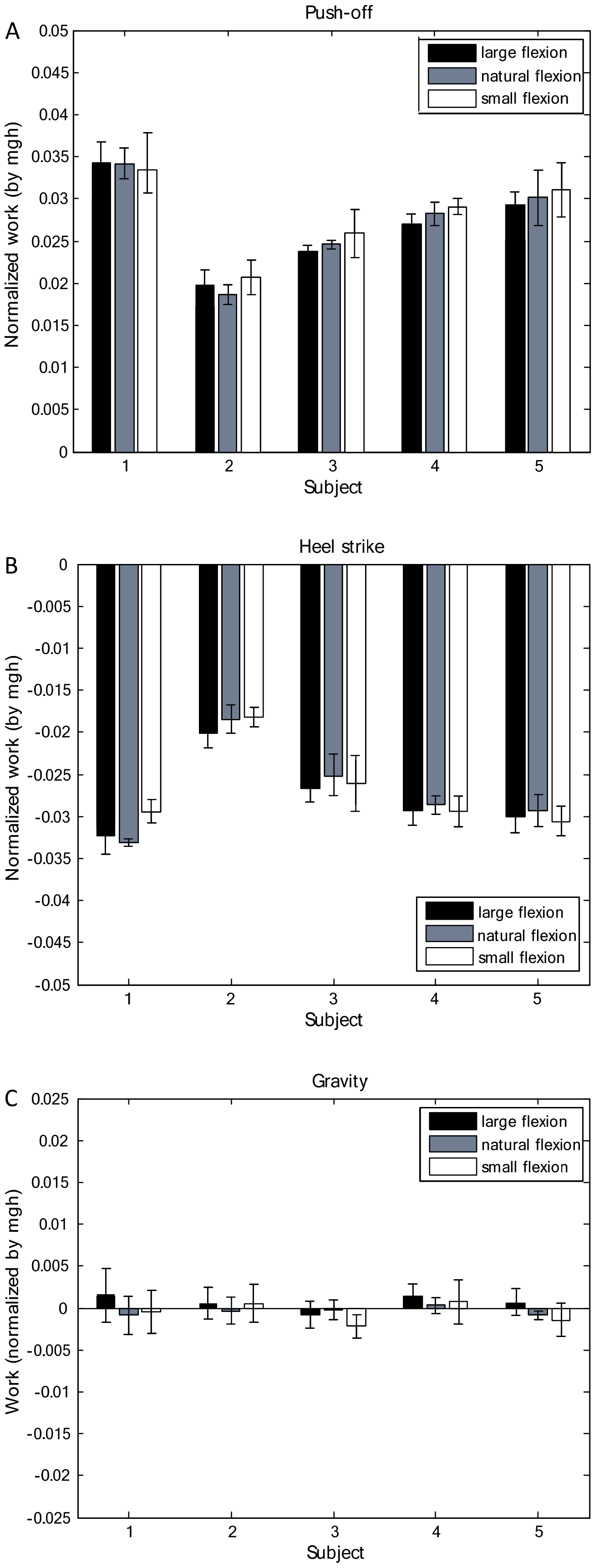


Fig. 7 Momentum directions by the trunk flexion change. (A) Pre-collision momentum, and (B) After-collision momentum

C. Mechanical Works on the COM

Donelan demonstrated that the mechanical work for the step-to-step transitions is a major determinant of the metabolic cost of human walking. [6]. In this paper, the mechanical works done on the COM during the step-to-step transitions were derived by each external impulsive force. Because the push-off, heel strike and gravitational impulse were not changed by the trunk flexion change, the mechanical works done on the COM performed by each impulse were also not changed by the trunk flexion change. Mechanical work by the hip torque was obtained using a generalized equation, as in (4).



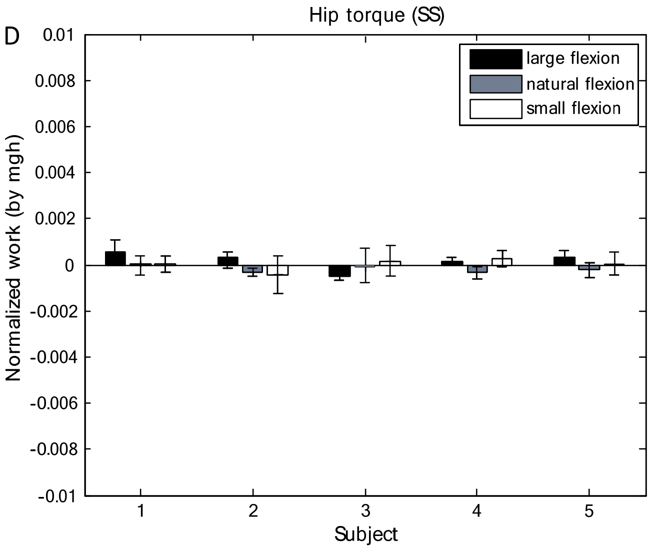


Fig. 8 Mechanical works done on the COM during the collision by the trunk flexion change. (A) Work done by the push-off, (B) Work done by the heel strike, (C) Work done by the gravity, and (D) Work done by hip torque

D.Geometric Analysis of the Impulse and Momentum

To verify data for analysis (either from the experiments or the computation), we draw an impulse-momentum diagram during the step-to-step transition as in Fig. 9. It shows that the pre-collision momentum of the COM moved upward due to the push-off, heel strike, and gravitational impulses through the step-to-step transition process. [8]

The error is calculated by the difference between mv^{+}_{com} and (mv^{-}_{com} + P* + G* + H*) and the percentage of the error is calculated by the ratio between the magnitude of the after-collision momentum and the error. The average percentage of the error is around 1.5% as summarized in Table II, which is remarkably consistent with the finite collision model [1], [2].

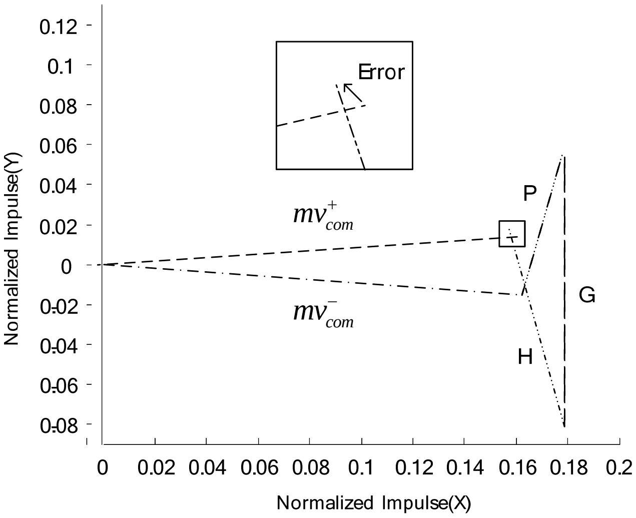


Fig. 9 Impulse-momentum diagram by the experimental data.

TABLE II
PERCENTAGE OF THE ERROR (UNIT: %)

Large flexion	Natural flexion	Small flexion
1.31 ± 1.42	1.35 ± 1.62	1.54 ± 1.19

IV. CONCLUDING REMARKS

Based on the finite collision model and experiments, we obtained several energetic features of loaded gait by the trunk flexion change. First, the magnitude of each impulse and the mechanical works done on the COM were seldom affected by the trunk flexion change, contrary to expectation in practice. Second, as the trunk flexion became larger, the direction of the pre-collision momentum moved downward. This implies that the movement of the COM influences only the direction of the pre-collision momentum while walking.

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REFERENCES

[1] Yeom, Jin, "Finite Collision Model for the Double Support Phase of Human Walking", *M.S. Thesis,* Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea, 2010.

[2] Yeom, Jin, "A gravitational impulse model predicts collision impulse and mechanical work during a step-to-step transition", *Journal of Biomechanics*, vol. 44, pp. 59-67, 2011.

[3] T. McGeer, "Passive dynamic walking," *The International Journal of Robotics Research*, vol. 9, pp. 62, 1990.

[4] M. Garcia, A. Chatterjee, A. Ruina, and M. Coleman, "The simplest walking model: Stability, complexity, and scaling," *ASME Journal of Biomechanical Engineering*, 1998.

[5] A. D. Kuo, "Energetics of actively powered locomotion using the simplest walking model," *Journal of Biomechanical Engineering*, vol. 124, pp. 113, 2002.

[6] J. M. Donelan, R. Kram, and A. D. Kuo, "Mechanical work for step-to-step transitions is a major determinant of the metabolic cost of human walking," *Journal of Experimental Biology*, vol. 205, pp. 3717-3727, 2002.

[7] A. D. Kuo, J. M. Donelan, and A. Ruina, "Energetic consequences of walking like an inverted pendulum: step-to-step transitions," *Exerc Sport Sci Rev*, vol. 33, pp. 88-97, 2005.

[8] P. G. Adamczyk and A. D. Kuo, "Redirection of center-of-mass velocity during the step-to-step transition of human walking," J Exp Biol, vol. 212, pp. 2668-78, 2009.

[9] F. J. Diedrich and W. H. Warren, Jr., "Why change gaits? Dynamics of the walk-run transition," J Exp Psychol Hum Percept Perform, vol. 21, pp. 183-202, 1995.

[10] L. Li and J. Hamill, "Characteristics of the vertical ground reaction force component prior to gait transition," Res Q Exerc Sport, vol. 73, pp. 229-37, 2002.

[11] S. J. Cuccurullo, editor, *Physical Medicine and Rehabilitation Board Review*. New York: Demos Medical Publishing, Inc., 2004.