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Pelvis Motion Analysis for Gait Phase Estimation toward Leg-dependent Body Weight Support at Different Walking Speed

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***Abstract*— Gait phase based body weight support can be an effective method for patients who possess different ability in each leg and who require different unloading forces between the affected and unaffected sides. To realize this concept, we proposed a gait phase estimation method from pelvic motion focusing on the feature of its quasi-periodic movement at constant walking speeds. In this study, we analyzed the relationship between the turning point of pelvic motion and the heel contact point at different walking speeds. The values of time lag were not constant at different walking speeds; rather they declined as walking speed increased. In addition, the results indicate that the turning points of lateral movement and vertical movement always occurred in advance of heel contact under 6.0 (km/h). Under this condition, the gait phase estimation method can be adopted if the time lag values at different walking speeds are prerecorded.**

I. Introduction

THE ability to walk is fundamental to living an independent life and also in the maintenance of physical and mental health. Body weight support (BWS) system applied to patients undergoing rehabilitation from spinal cord injury, stroke, or fracture of the femur, while walking on a treadmill or over ground, can facilitate rehabilitation.

Several motor-actuated devices have been developed in relation to this work. Frey et al. [1] and Glauser et al. [2] designed and constructed a partial BWS system that constantly monitors the provided unloading force and takes immediate action to maintain the unloading force within the limits of a specified unloading force profile. With these system, the unloading force can be kept constant during the entire gait cycle or can be varied in a controlled manner within the gait cycle to facilitate walking. The desired support level can be changed simultaneously with events or conditions that occur during walking based on the gait phase. To allow a faster transition from low to high or high to low unloading force, a time optimal control, featuring a high motor shaft velocity and duration adaptation, replaces the error feedback term for a short time. However, when considering the movable BWS system for over ground walking, there are power and space limitations with respect to the actuators. As one solution to this problem, a feed forward control method is effective even when using an actuator with limited performance of motor shaft velocity and output torque. Based on this concept, we propose a "leg-dependent force control" combined with feed forward control and gait phase estimation [3]. The approach of gait phase estimation involves the measurement of pelvic motion which is assumed to be periodic, and the estimation of heel contact timing in advance from the time lag between feature point of pelvis movement and heel contact point. However, this method has been tested only at constant walking speeds since the effects of changes in walking speed on the time lag have not been studied.

The purpose of the present study is to reveal the relationship between feature points of the pelvic movements and heel contact points on time scale at different walking speeds, and the applicable scope of the proposed gait phase estimation method with respect to walking speed.

The remainder of this paper is organized as follows: Section II describes concept of gait phase estimation method. Section III presents analysis of pelvic movements. Finally, section IV summarizes the conclusions of this study and outlines future work to be conducted.

II. Concept

We have developed a BWS system with pelvic support (Fig. 1 left). Since the designed pelvic support has 5 degrees of freedom, excluding the translation in the Y-axis as defined in Figure 2 (a), it allows for natural walking motions of the pelvis and sensing of pelvic motion with mounted sensors.

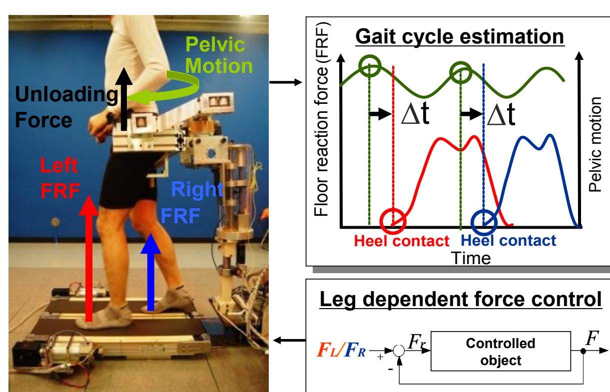

Fig. 1 Concept of leg-dependent force control method. Note that F is unloading force. F_L and F_R are target unloading force for left side and right side respectively. Δt is the time lag between the peak of the pelvic motion and heel contact

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To estimate the gait phase from pelvic motion, a relationship between pelvic motion and the gait phase must be first obtained. In particular, since leg impact is maximized immediately after heel contact, the timing of heel contact must be detected in advance of pelvic motion. Based on the gait phase estimated by this method, the target unloading force for body weight support can be adjusted. (Fig. 1) Since the pelvis motion is periodic, the wave patterns of the motion must have a turning point such as a local minimum or a local maximum before heel contact of the left or right leg, respectively. The time lag between the peak of the pelvic motion and heel contact is defined as Δt. Although Δt has been obtained at constant walking speed, the change in Δt at different walking speeds has not been studied. A related publication [4] details a method to describe gait as a sequence of states to overcome the speed change in walking. However, its application to walking speeds is not described and only joint angles in the sagittal plane are considered.

The focus of this paper is to analyze the effect of different walking speeds on the relationship between pelvic motion and gait phase. This objective was met by measuring Δt, with the ultimate goal of realizing "leg-dependent force control" at over-ground terrain where walking speed varies.

III. Analysis of Pelvis Movement

A. Experimental methods

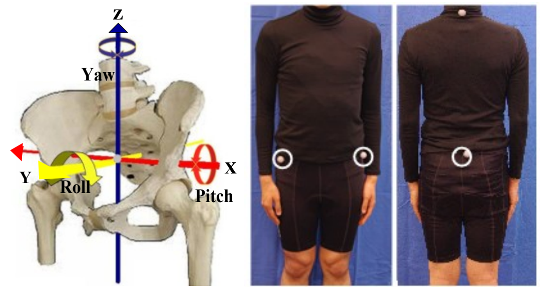
As defined in Figure 2 (a), pelvis motion comprises 3 translational movements such as side-to-side (x), forward-and-back (y), up-and-down (z), and 3 rotational movements such as pelvic tilt (pitch), rotation (yaw), and obliquity (roll). Characteristic analyses were conducted in order to investigate whether or not each movement excluding y-axis translation has feature point to be extracted. Subsequently, pelvis movement analysis at different walking speeds was carried out.

The subject of these preliminary experiments are healthy young males with a body weight was 65 (kg). The walking speed was chosen from 1.0 - 6.0 (km/h) based on the possible range of walking speeds. The stride was fixed to step on force plates. Heel contact during the gait cycle was determined from the floor reaction force with a threshold of 15 (N). Floor reaction force was measured using a floor reaction force meter (AMTI, OR6-7 2000, cutoff frequency for the low-pass filter: 10.5 (Hz)). The pelvic motion was measured at 100 Hz by means of an eight camera VICON system (Vicon612, Oxford Metrics Ltd., sampling frequency 100 (Hz), and accuracy 1(mm).). Three body markers were attached on right and left superior anterior iliac spine, and sacral bone. (Fig. 2 (b)) Measured floor reaction force and the pelvic motion were synchronized with a server PC.

B. Characteristic Analysis of Pelvis Movement

To obtain reliable time lags between the timing of feature points from pelvis movements to that of heel contact, the repeatability of the measured pattern of pelvic movements can be demonstrated.

Figure 3 shows the time series graph of pelvic movement.



(a) Axial composition (b) Markers' configuration

Fig. 2 Definition of axial composition and the markers' configuration on pelvis

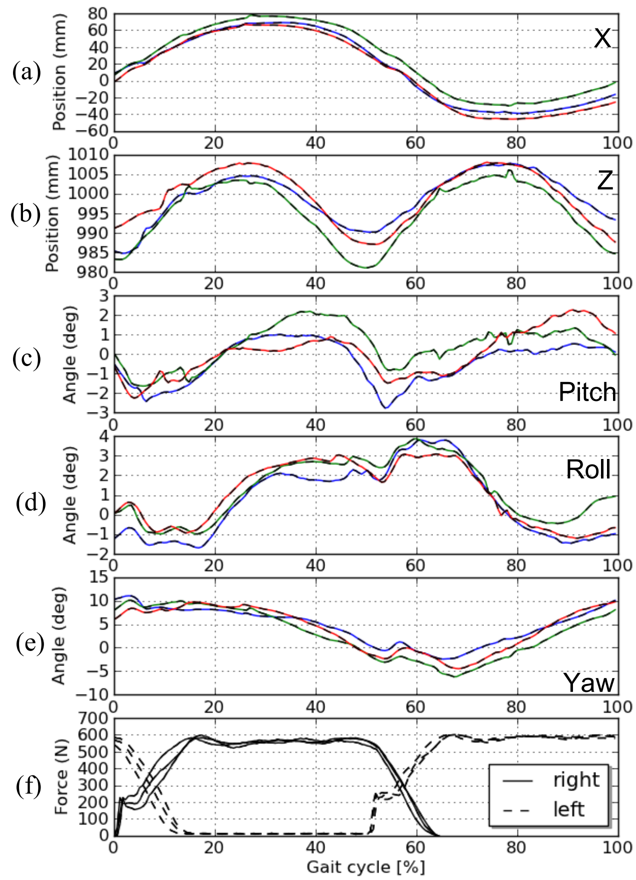


Fig. 3 Time series graphs of pelvic movement. Graphs "X" and "Z" show the position of pelvis during lateral and vertical movements, respectively. Pitch axis, Roll axis, and Yaw axis are illustrated in plots (c)-(e). Graph (f) shows the floor reaction force. This data was obtained at 2.0 (km /h)

With respect to translation, both lateral and vertical movement share similar sine wave characteristics. The lateral movement in a walking cycle comprises 1 cycle, whereas the vertical movement in a walking cycle consists of 2 cycles. The lateral movement within a walking cycle is a reciprocal movement that results from the weight shift towards the stance leg that allows the swing leg to be lifted, and vice versa thus accounting for the single cycle observed. The vertical movement within a walking cycle includes 2 reciprocal motions caused by movement of right leg and left leg. The amplitudes and the centers of oscillation of these patterns were varied slightly over walking cycles, however significant phase shifting was not observed by comparison of peaks in

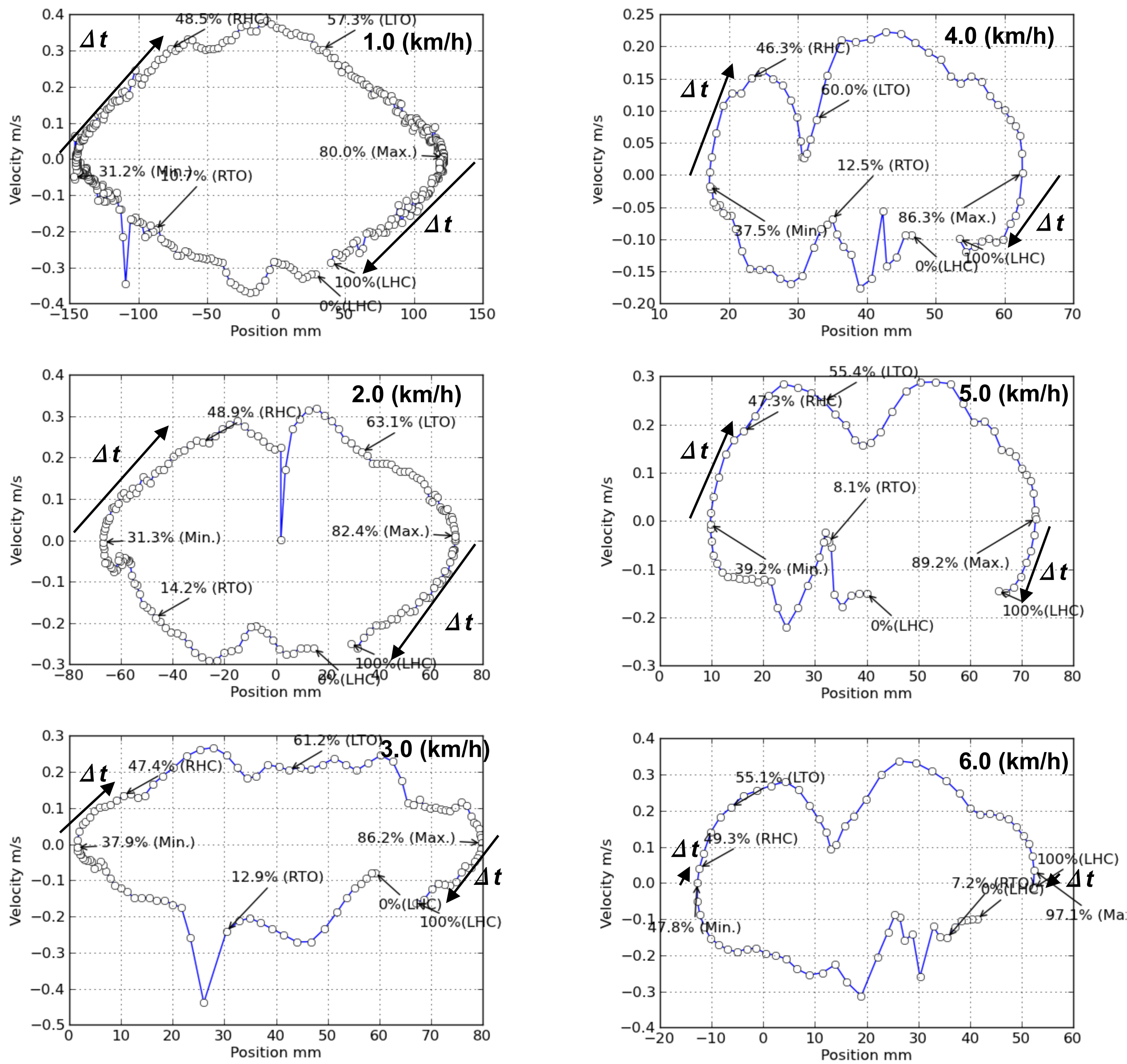


Fig. 4 Phase–plane plots of pelvic lateral movement. (Top left: 1.0 (km/h), middle left: 2.0 (km/h), bottom left: 3.0 (km/h), top right: 4.0(km/h), middle right: 5.0 (km/h), bottom right: 6.0 (km/h))

the patterns. The results obtained suggest that the lateral and vertical movements may be useful for gait phase estimation.

By contrast, rotation movements are considerable more complex. Many peaks can be seen in the patterns, which include other frequency elements from those mentioned above. For peak detection, these frequency elements need to be identified and filtered to smoothen the data, or curve fitting method is required. As a first step, we focused on the translational movements for analysis in this study.

C. *Pelvis Movement Analysis at Different Walking Speed*

The objective of this analysis is to determinate the variation of the time lag between the feature points from pelvis movements and heel contact point at different walking speeds. We use the turning point in the patterns as feature points to estimate the gait phase, where the derivative, that is velocity, changes from negative to positive or vice versa. Figure 4 illustrates the phase diagram of lateral movement which allows us to visualize the relationship between position and velocity and also the effect of the change in walking speed. The lateral axis indicates the position of lateral movement and the vertical axis represents the velocity. The graph show 1 gait cycle which starts with the plot of left leg's heel contact point annotated "0% LHC" and ends with the plot of left leg's following heel contact point annotated "100% LHC." The turning points of position (Min. or Max.) and right leg's heel contact points obtained from floor reaction force (RHC) are

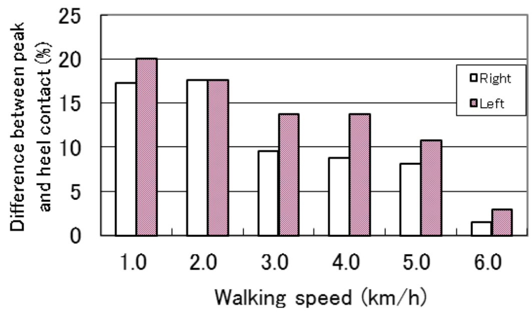


Fig. 5 Difference between peaks of the pelvis lateral translation and the heel contacts (*Δt)*

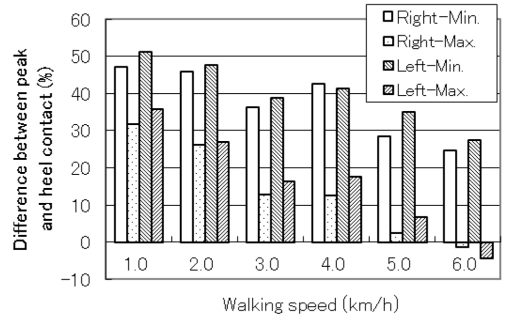


Fig. 6 Time lag between peaks of the pelvis vertical translation and the heel contacts (*Δt)*

plotted with the percentage normalized to 100% of the gait cycle. The time lags between the turning points and heel contact point are indicated with *Δt.* at all walking speeds, that is, the turning point always occurred before the heel contact point. However, the time lag between the turning points and heel contact point varied according to walking speed.

Figure 5 shows the results of time lag between peaks of the pelvis lateral and vertical movements, and the heel contacts (*Δt*).

Two significant gaps can be seen in left *Δt* and right *Δt* at the different walking speeds. The first gap from 2.0-3.0 (km/h) may corresponds to the difference between static and dynamic walking. The second gap can be observed between 5.0 and 6.0 (km/h). Left *Δt* was 1.5 (%), and right *Δt* was 2.9 (%) at 6.0 (km/h), which is significantly smaller when compared to the analogous values at 5.0 (km/h). This second gap may correspond to the difference between walking and running

Despite the differences in *Δt* between right and left, the gait phase estimation method is still viable because *Δt* for right side and *Δt* for left side can be set respectively.

Figure 6 shows *Δt* of the vertical movement of the pelvis. Since the vertical movement involves 2 cycles in a walking cycle, there are four turning points. Each turning point can be defined as follows:

Right – Min.: *Δt* from minimum points to right heel contact
Right– Max.: *Δt* from maximum points to right heel contact
Left – Min.: *Δt* from minimum points to left heel contact
Left – Max.: *Δt* from maximum points to left heel contact

The results demonstrate that *Δt* declined overall. Some *Δt* values such as Right – Max at 3.0 (km/h) and 4.0 (km/h), and Left - Max at 3.0 (km/h) and 4.0 (km/h), also behaved similarly. A noteworthy results is that the sequence of the turning point in vertical movement and heel contact point changed at 6.0 (km/h), that is, the turning point appeared after heel contact point and *Δt* had a negative value. This can be attributed to the phase shift between the vertical movement and heel contact. In this scenario, the gait phase estimation method is not applicable to the vertical movement data because the feature point cannot be obtained in advance of heel contact.

In summary, it appears that *Δt* values were not constant but changed according to the walking speed. The values of *Δt* decreased but remain positive under 6.0 (km/h). The fact that the range of walking speeds of the patient will not exceed 5.0 (km/h) under clinical supervision, suggests that the gait phase estimation method is viable if *Δt* values at different walking speeds are prerecorded and appropriately adjusted.

IV. CONCLUSIONS

Pelvic motion during gait at different walking speeds was analyzed to reveal the relationship between the pelvis movement and the gait phases toward leg-dependent force control during BWS. We focused on the lateral and vertical movements out of the six degrees of freedom in pelvic motion. The results demonstrated that *Δt* values were not constant and varied with different walking speeds. At 6.0 (km/h), *Δt* exhibits significantly different values from those values under 6.0 (km/h). We can reasonably assume that in a clinical scenario the walking speed of the patient will not exceed 5.0 (km/h). Thus the gait phase estimation method can be adopted if *Δt* values at different walking speeds are prerecorded and suitably adjusted.

Future work will involve testing our proposal using treadmill. In this work, floor reaction force plates were used, which places limits upon the stride and the walking distance measured. Thus, continuous pelvis movements with different cadence can be recorded on treadmill. In addition, further analysis with a sufficient number of subjects including patients who have asymmetric gate or less pelvic movement will be conducted to validate this method.

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