Biomechanical Perspective on Effect of Angle in Arm Swing Movement on Vertical Ground Reaction Force for Gait Improvement

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***Abstract*— This study focuses on arm swinging movements in gait for active self-healthcare. However, most of the research on arm swing movements is clinical approach and biomechanical mechanisms of why these movements are effective are not well understood. Therefore, this study aims to biomechanically elucidate the coupled process of arm swing and lower limb movement. This coupled process can lead to an effective gait according to his/her gait at the time. In this paper, we focus on the bimodality of vertical ground reaction force, which is also used for gait evaluation in clinical practice. The purpose of this paper is to experimentally clarify how the bimodality of vertical ground reaction force varies with arm swing, and to determine mechanistically what coupled processes are responsible for this variation. The experiment is carried out with four volunteers. In the experiment, each volunteer performs six different gait conditions. In these experiments, the ground reaction forces and mechanical parameters of each body segment are measured. The results of the analysis showed that an increase in the angle of lateral pelvic tilt and the vertical ground reaction force increased in the valleys and decreased in the part of late peaks, as the angle of arm swing increased. The angle of lateral pelvic tilt also showed a change in value at the same time as the late peak of the vertical ground reaction force. This suggests that the bimodality of vertical ground reaction force is related to the pelvic lateral tilt movement induced by arm swing.**

Keywords - Biomechanics; Pelvic angle; Arm movement; ground reaction force .

I. INTRODUCTION

Recent advances in medical care have led to the aging of the population in many developed countries [1]. In Japan, according to the 2021 Simple Life Chart published by the Ministry of Health, Labour and Welfare, the average life expectancy for men is 81.47 years and 87.57 years for women, and the percentage of people reaching 90 years of age is 3.9 times higher for men and 3.3 times higher for women compared to 1980[2]. These data suggest that society will continue to age further. Under these circumstances, the social issue is to reduce the gap between average life expectancy and healthy life expectancy. Walking is often viewed as the easiest way to solve this problem and as it has a low risk of disability even for people with knee or back diseases [3]. Therefore, walking has been studied from various approaches. Research on the effects of arm swinging has revealed changes in lower limb muscle activity [4], increased stride length [5][6], increased maximum walking speed [7], and improved stability in walking [8]. However, these studies are clinical approach, and it is not known why arm swing movements are effective. Consequently, depending on an individual's gait, changing the arm swing movement may not result in an effective gait, such as no change in walking speed or stride length, or conversely, a worsening of walking speed or stride length. Therefore, research is conducted from the point of view of biomechanics to clarify the factors that contribute to the effectiveness of walking. Most biomechanical studies that focus on arm swing have discussed the stability and symmetry of gait [9], but few have discussed how arm swing leads to an increase in walking speed and stride length. Hence, this study aims to biomechanically elucidate the coupled process of arm swing and lower limb movement. This coupled process can lead to an effective gait according to his/her gait at the time.

As a first step, this article focuses on the vertical ground reaction force, which is one of the most important indices in the evaluation of walking behavior [10] and is related to the propulsive force of walking. It is clinically known that the vertical ground reaction force is bimodal in normal gait and the bimodality of force changes with differences in gait. For example, the difference between the peaks and valleys of the bimodality of vertical ground reaction force increases with increasing walking speed [11], and the early peaks become larger, and the valleys and late peaks become smaller with increasing stride length [12], indicating a close relationship between walking motion and the bimodality of vertical ground reaction force. Additionally, the bimodality of vertical ground reaction force has been reported to be lost with aging due to a decrease in walking speed [13]. Therefore, the purpose of this report is to experimentally clarify how the bimodality of vertical ground reaction force is affected by the arm swing movement and to clarify the coupling between the arm swing movement and the vertical ground reaction force by observing the mechanical parameters. In the experiment, an optical motion capture system and a ground reaction force meter are used to measure and analyze the motion of each segment and the values of the ground reaction force induced by the swing of the arm setting the angle of arm swing condition.

Section II describes the conditions and methods of the arm swing experiment, Section III presents the results of the analysis, Section IV discusses the results of the analysis, and Section V summarizes this paper and discusses future developments.

II. EXPERIMENTAL METHOD

The purpose of this experiment is to measure the mechanical parameters and the vertical ground reaction force of each segment during gait to clarify the effect of adjusting the angle of arm swing on the vertical ground reaction force values. This experiment will focus on steps 5-7, which is the steady-state gait. The purpose and contents of this study were explained to four volunteers (age: 22.5±0.5 [years], height: 1.70±0.03 [m], weight: 66±2 [kg]) who gave oral and written consent. In addition, this study was approved by the Ethical Review Committee. There are six gait conditions: (a) walking natural without awareness of arm swing, walking with arms attached to the body (b) without swinging arms, (c) backward arm swing, (d) large backward arm swing, (e) forward arm swing, and (f) large forward arm swing, with five trials in each condition. In the case of a large arm swing, the upper body motion would differ between backward and forward swings, the effect of the upper body on the lower limbs would also be different. For the large arm swinging movement, the volunteer is instructed to raise his arms to a level parallel to the ground within a comfortable range. In addition to arm swing, we do not give any instructions on stride length or walking speed, considering the ease with which the volunteer can walk. In all walking conditions, except for natural walking and walking without swinging arms, volunteers practice walking five times before each trial to familiarize themselves with the walking motion.

To obtain a large number of mechanical parameters, such as muscle activity and joint angles, from body data, the musculoskeletal modeling simulation AnyBody (AnyBody Technology), one of the analysis software, was used. The 3D positional coordinates of the markers are measured by taking pictures using the MAC3D system (Motion Analysis Corporation), which is an optical motion capture system. Twelve cameras with a sampling frequency of 100 [Hz] are used. The measured marker positions are denoised with a low-pass filter of 6 [Hz]. Three force plates (TF-4060 and TF-6090 manufactured by Tec-Gihan) were used to measure reaction force values, with the right foot, left foot, and right foot moving on one force plate in the order of 5 to 7th step of the experimental volunteer, respectively. After the above measurements, a total of 119 data, excluding one trial of the forward arm swing condition for Volunteer A, whose data were found to be incomplete, are used as input data for AnyBody analysis.

III. RESULTS

First, the results of the vertical ground reaction force values are shown. Figure 1 shows the vertical ground reaction force values for each randomly selected condition for volunteer D, representing Volunteers B~D who showed similar tendencies, and Volunteer A, who showed different tendencies from the other collaborators. The abscissa axis indicates the time when the right foot lands on the ground as 0[%] and the time when the right foot leaves the ground as 100[%].In natural walking, an early peak appears in the first half of the stance phase (around 20[%]), a valley in the second half of the stance phase (around 40[%]), and a late peak in the terminal stance phase (around 80[%]).

Table I summarizes the mean values of the peaks and troughs of the vertical ground reaction force for each volunteer and condition. The characteristics of the vertical ground reaction force values for each volunteer, as seen in Figure 1 and Table 1 are shown below.

For volunteer A, the anterior peak values increased in the swinging of the large arm swing walking compared to the natural walking condition. For volunteer B, the peak values decreased and the valley values increased with increasing angle of arm swing compared to natural walking. However, compared to volunteers C and D, who showed a similar tendency, the vertical ground reaction force fluctuation due to an increase in the angle of forward arm swing was reduced by a small amount. For volunteer C, the initial peak tended to increase as the arm swing angle became more forward, but decreased in the largely backward arm swing condition. The late peak decreased with increasing arm swing angle. For volunteer D, the value of the early peak increased with increasing backward angle of arm swing, but decreased with increasing forward angle of arm swing.

In all volunteers, the late peak values decreased as the arm swing angle increased both forward and backward. Furthermore, the bimodality of vertical ground reaction force values tended to be lost in the rearward arm swing condition due to the increase in the valley and the late peak values.

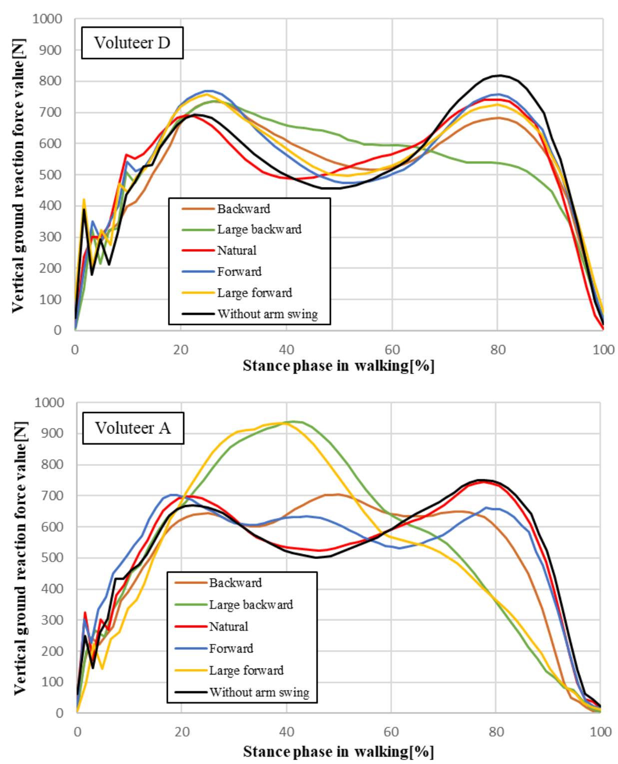

Figure 1. Comparison of vertical ground reaction force values for one trial of each gait condition during the stance phase.

TABLE I. BIMODAL AVERAGED VERTICAL GROUND REACTION FORCE VALUES FOR EACH GAIT CONDITION DURING THE STANCE PHASE. VALUES IN BOXES ARE INITIAL PEAK/VALLEY/LATE PEAK.

ID	Volunteer A	Volunteer B	Volunteer C	Volunteer D
a	687/537/734	634/492/732	712/473/726	719/475/765
b	688/505/747	590/475/750	706/461/760	724/442/807
c	701/639/662	624/509/710	714/508/684	731/522/701
d	926/596/575	614/570/674	709/560/645	788/535/583
e	683/613/670	613/498/721	724/499/692	748/481/758
f	867/612/596	610/525/712	738/520/658	716/521/716

The results of the pelvic lateral tilt angles are shown next. Figure 2 shows the pelvic lateral tilt angles for each randomly selected condition for Volunteer D, who represented Volunteers B~D who showed a similar tendency, and Volunteer A, who showed a different tendency from the other volunteers. Pelvic lateral tilt angle 90 ° and is the pelvic tilt angle horizontal to the ground; When the pelvis is tilted anticlockwise (ACW) as viewed from the direction of travel, the value tends toward the minus side.

Since symmetric movement between the stance and swing phases and similar changes can be observed in the waveforms, Table 2 summarizes the mean values of the troughs and peaks in the early phase and the troughs in the late phase of the stance phase.

The characteristics of each volunteer's transverse pelvic tilt angle seen in Figure 2 and Table 2 are shown below. In the

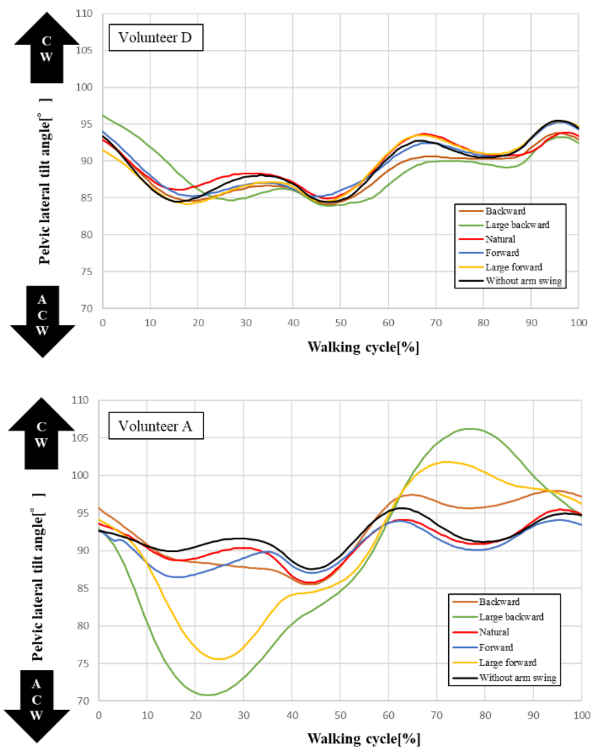

Figure 2. Lateral pelvic tilt angle for one trial of each gait condition in one gait cycle.

TABLE II. MEAN PELVIC LATERAL TILT ANGLE FOR EACH GAIT CONDITION DURING STANCE PHASE. VALUESV IN BOXS ARE EARLY VALLEY/PEAK/LATE VALLEY.

ID	Volunteer A	Volunteer B	Volunteer C	Volunteer D
a	90.2/92.7/87.4	87.1/88.2/82.1	87.0/89.2/84.8	85.1/88.2/84.9
b	88.8/91.1/86.5	87.8/89.1/82.5	86.6/88.5/84.9	84.7/88.6/85.0
c	86.0/87.1/85.2	86.3/87.5/81.6	86.0/87.6/83.8	85.1/86.4/84.3
d	72.7/80.1/80.1	87.2/88.6/80.7	86.3/87.6/82.3	85.2/85.9/83.4
e	87.8/90.1/86.8	86.7/88.1/82.5	87.1/89.0/84.7	84.9/87.5/84.8
f	81.7/84.6/83.9	86.7/88.2/82.3	86.1/87.6/83.0	85.7/88.0/85.6

case of volunteer A, the peak tended to disappear in the large arm swing condition, and the lateral tilt angle also decreased. For volunteer B, the peak values decreased and the valley values increased with increasing angle of arm swing compared to natural walking. For volunteer C, the difference between the early valleys and peaks tended to decrease as the angle of swing of the arm increased, and the late valleys showed a decreasing trend compared to natural walking. For volunteer D, the trends of the early valleys and peaks were similar to those of volunteer C. However, the late valleys decreased with increasing backward angle of arm swing, but increased with increasing forward angle of arm swing.

In all volunteers, the late valleys tended to decrease with increasing angle of arm swing compared to natural walking.

Finally, the vertical ground reaction force values and the pelvic lateral tilt angle under the same conditions are shown in Figure 3.

As shown by the red dashed line in Figure 3, the late peak of vertical ground reaction force and the timing of the decrease in the pelvic lateral tilt angle were identical for all volunteers and all conditions. The data showed that the minimum value and the timing of the pelvic lateral tilt angle were the same in the late peak of the vertical ground reaction force and that the pelvic lateral tilt angle tended to lose its bimodality in the data of ground reaction force values in which bimodality was lost, suggesting that the pelvic lateral tilt angle affected the late peak of vertical ground reaction force values.

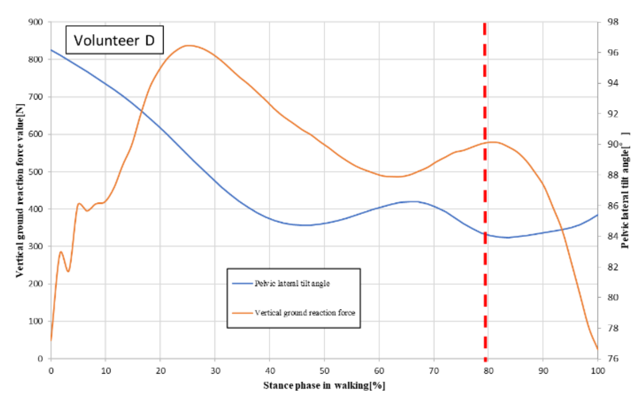

Figure 3. Lateral pelvic tilt angle and vertical ground reaction force values during the stance phase under the same conditions.

IV. CONSIDERATION

The biomechanical relationship between the arm and the bimodal change in the lateral pelvic tilt angle and the vertical ground reaction force is discussed. Regarding the change in the pelvic lateral tilt angle, the shoulder on the side where the arm is forward is tilted downward due to the swing angle of the increase in the backward arm. The pelvis moves upwards as a reaction to this shoulder tilt, which is thought to increase the angle of lateral tilt.

Regarding the relationship between vertical ground reaction force and pelvic adduction, vertical ground reaction force is correlated with acceleration of the body's center of gravity [14]. This suggests that the vertical ground reaction force at the stance terminal phase also decreased because the sacrum, which is considered the center of gravity of the human body, moved up and down due to the lateral pelvic tilt.

V. CONCLUSION

The purpose of this paper is to experimentally clarify how the bimodality of vertical ground reaction force changes with arm swing and to clarify mechanically what kind of coupling caused this change. In the experiment, six conditions of arm swings were set up and the mechanical parameters of each segment and vertical ground reaction force were measured for each gait condition. Experimental analysis showed that the lateral tilt angle of the pelvis changed as the arm rotation angle increased, and the bimodal disappearance of the vertical ground reaction force was observed.

The results of the present paper suggest that the lateral pelvic tilt motion induced by arm swing is involved in the bimodality of vertical ground reaction force. Therefore, it is a future task to clarify the coupling process between the lateral pelvic tilt angle and the vertical ground reaction force. As an approach to solving the problem, mechanical parameters are observed for the segments of the pelvis and lower extremities.

Furthermore, to clarify the coupling between the upper and lower limbs, we will try to approach not only from the joint angles, but also from the muscle activities induced by arm swing. The future research will include the development of an application that provides biofeedback of effective movement indicators to each individual based on the coupled process.

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