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Faster Detection of Step Initiation for the Lower Limb Exoskeleton with Vertical GRF Events

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Abstract – We propose a new approach called as a peak time approach for faster detection of step initiation for the lower limb exoskeleton. As faster detection of step initiation is an important criterion in evaluating the lower limb exoskeleton, many studies have investigated approaches to detect step initiation faster, including using electromyography, the center of pressure, the heel-off time and the toe-off time. In this study, we will utilize vertical ground reaction force events to detect step initiation, and compare our approach with prior approaches. Additionally, we will predict the first step's heel strike time with vertical ground reaction force events from multiple regression equations to support our approach. The lower limb exoskeleton should assist the operator's movement much faster and more reliably with our approach.

Keywords: The lower limb exoskeleton, Step initiation, Ground reaction force

1. Introduction

With the augmented strength provided to the operator, the lower limb exoskeleton has received considerable attention from the military and rehabilitation industries over the past several decades [1-4]. The operator can not only walk more easily, but also walk further for less metabolic cost because of the augmented strength from the lower limb exoskeleton. It is important for the lower limb exoskeleton to assist the operator's movement as soon as possible to achieve this feat. Consequently, many studies have been conducted to detect the operator's movement intention [5-7]. In particular, many studies investigating the detection of step initiation have been conducted using electromyography (EMG), the center of pressure (COP), the heel-off time and the toe-off time.

The approach using EMG utilizes bio-electrical signals to detect step initiation [8]. This approach can detect step initiation prior to the occurrence of any visible movements and is the fastest approach for detecting step initiation [9-10]. However, the problems associated with use of the EMG approach, such as low reliability, long calibration time for each person and so on, indicate limitations in the further development of the exoskeleton more with this approach. The robot suit Hybrid Assistive Limb (HAL) utilizes the EMG approach.

The approach using the COP detects the trajectory event of the net COP from the start to release event of the swing leg [11]. It can detect step initiation faster than the toe-off approach. However, this approach is only suitable for helping patients maintain balance during medical therapy or rehabilitation. As a result, it has mainly been applied to human gait analysis for the control of balance.

The heel-off approach is the latest approach used for detecting step initiation, and it is based on the heel-off time [12]. This approach utilizes the heel-off time generated from ankle markers or force plates, and it is the fastest approach for detecting step initiation without using any bio-electrical signals for the lower limb exoskeletons. However, it is not reliable. The heel-off approach needs additional methods to detect step initiation reliably, such as a complicated learning algorithm or more sensors. The RoboKnee utilizes the heel-off approach [13].

The toe-off approach detects step initiation based on the toe-off time [14]. It is more reliable and easier to measure, albeit slower, than the heel-off approach. The BLEEX utilizes the toe-off approach [15].

This study proposes a new approach called as a peak time approach for detecting step initiation faster without using any bio-electrical signals. We analyzed the human gait from a quiet standing position to the first step with motion capture devices, including three force plates. As a result, we found that the vertical ground reaction force (GRF) events respond faster than any kinematic movements. We also found that two particular vertical GRF events occur before any visible movements occur. Using these particular vertical GRF events, we detected step initiation faster than other approaches without using any bio-electrical signals. In addition, we predicted the heel-strike time for the first step, which had no difference between the measured heel-strike time to support our approach.

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2. Methodologies

2.1 Subjects

There are three healthy subjects (three males) with ages of 25, 28 and 24 years old volunteered to participate in this study. Table 1 shows the subjects' body parameters. The subjects did not have postural problems and gave informed consent approved by the Institutional Review Board of KAIST prior to participating in the experiment. The subjects' average height and weight were 1.74 ± 0.05 m and 70 ± 7 kg, respectively.

2.2 Equipment

For the detection of heel-off, ankle kinematics was sampled at 200 Hz with motion capture cameras (Motion Analysis, Hawk®). The optical markers were located on the sacral, both sides of the pelvis, both knees, and both ankles. Data from the optical markers were 5^{th}-order Butterworth low-pass filtered with a cutoff frequency of 10 Hz for analysis of the ankle kinematics. The GRF events from the stance phase to the first step were measured using three force plates (AMTI, AccuGait®) at 200 Hz sampling frequency [16]. The GRF data were 5^{th}-order Butterworth low-pass filtered with a cutoff frequency of 30 Hz, and a vector product of the external forces (N) was calculated from the mechanical power (N-m/s) applied by the GRFs [17]. The cutoff frequencies used to filter the optical marker and GRF data, 10 Hz and 30 Hz were optimized to remove noise with consideration of human gait pattern (3~5 Hz for the kinematic data, 10~15 Hz for the GRF data) [16, 18-19]. The system of force plates and motion capture devices used in this study is shown in Fig. 1, while Fig. 2 shows the arrangement of three force plates for this study.

Table 1. Subjects' body parameters.

	Age(years)	Height(m)	Weight(kg)
Subject 1	25	1.72	70
Subject 2	28	1.79	77
Subject 3	24	1.74	65

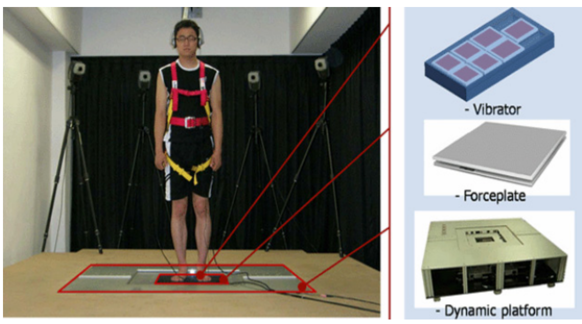

Fig.1. The system of force plates used, which consisted of vibrators, force plates and a dynamic platform [17].

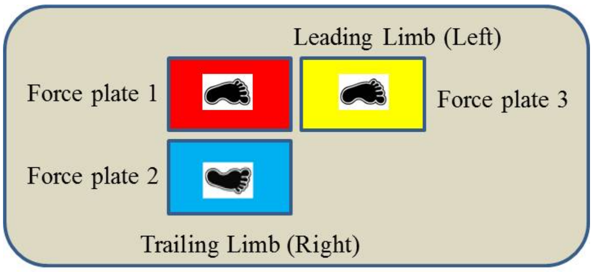

Fig. 2. The arrangement of the three force plates

2.3 Measurement protocol

The subjects stood with both feet on force plates. The subjects started walking with the left foot on a 10-m-long, 1-m-wide walkway, with instructions to walk with their preferred step velocity. The instruction to walk was given to the subjects by the experimenter. The Subjects practiced the measurement protocol sufficiently before measurements were recorded. Each subject performed three trials starting with the left foot, thus, a total of 9 data sets were collected.

2.4 Detection algorithm

We attempted to capture particular events, including the vertical GRFs, the trajectory of the net COP, the heel-off and the toe-off. The vertical GRF events were measured with the force plates. We attempted to capture particular GRF events to determine which approach can detect the step initiation the fastest. The trajectory event of the net COP was calculated from the force plates measurements according to Eq. (1), as follows [11];

$$COP_{net(x,y)} = COP_{l(x,y)} \frac{F_{z,l}}{F_{z,l}+F_{z,t}} + COP_{t(x,y)} \frac{F_{z,t}}{F_{z,l}+F_{z,t}} \quad (1)$$

$COP_{l(x,y)}$: the COP of the leading limb
$COP_{t(x,y)}$: the COP of the trailing limb
$F_{z,l}$: the vertical GRF on the leading limb
$F_{z,t}$: the vertical GRF on the trailing limb

The heel-off events were measured with the force plates and optical ankle markers. Heel-off occurs when the heel is lifted just before the front end of the foot leaves the ground [12]. The toe-off events, which occur when the toes left ground [14], were measured with the force plates. The toe-off events can be determined easily, when the vertical GRFs drop to zero.

2.5 Multiple regressions

To support our approach, we performed regression analysis on the 9 data sets collected to predict the heel-strike time for the first step using Eq. (2) as follows;

$$\hat{Y}_i = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_k x_{ki} + \varepsilon_i \quad (2)$$

where, $\hat{Y}_i$ is the first step's heel strike regression time, x_{ki} is the vertical GRF event time, and β_k is the regression coefficient, that determines the relationship between y_i (the measured first step's heel-strike time) and $\hat{Y}_i$. ε_i is the residual between y_i and $\hat{Y}_i$ defined as the normal distribution $N(0,\sigma^2)$. Meanwhile, β_k is calculated using the least squares method, which minimizes the sum of the squares of the residual between y_i and $\hat{Y}_i$, according to Eq. (3), as follows;

$$Q = \sum_{i=1}^{n} \left\{ y_i - \left(\beta_0 + \beta_1 x_{1i} + \cdots + \beta_k x_{ki}\right)\right\}^2 \quad (3)$$

where, Q is referred to as the sum of the square of the residual between y_i and $\hat{Y}_i$. Q can be minimized by taking the derivatives with respect to each of the unknown parameters (β_k) setting the resulting expressions (Q) equal to 0, and then simultaneously solving the equations to obtain the parameter estimates β_k [20].

3. Results

3.1 Response time for step initiation

We compared the response time between the GRFs and other kinematic movements to determine which approach detected step initiation the fastest with force plates and a motion capture device. As illustrated in Fig. 3 and Table 2, the response time of the GRF was faster than the center of mass (COM), the knee joint whose response was faster than the other joints (the pelvis and ankle), the angle displacement and the angular acceleration. The results clearly indicate that particular GRF events are important measurements that can be utilized to detect step initiation faster than previous approaches.

3.2 Vertical GRF events for detection of step initiation

We captured the two vertical GRF events from the three force plates for each of the three subjects, as illustrated in Fig. 4. The first vertical GRF occurred at the intersection between the left foot and the right foot. Second, we observed that the vertical GRF of the first step decreased rapidly after the peak value, which was followed by the heel-off and the toe-off. These events always occurred

Table 2. The response time of the GRF and other kinematic movements for step initiation

	GRF	COM	Ankle	Knee	Pelvis
Response	0.18	0.25	0.88	0.43	0.465
Error (%)	1.90	1.40	2.65	2.10	2.41

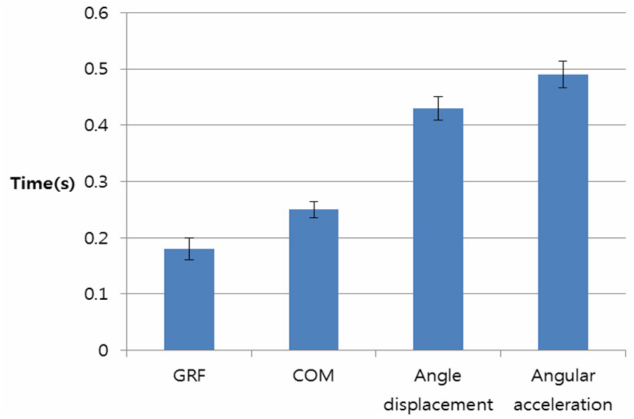

Fig. 3 Comparison of the response times between the GRFs and other kinematic movements.

Table 3. Comparison of the time to detect step initiation between the peak time (proposed) approach and other approaches.

Trial	Proposed (sec)	COP (sec)	Heel-Off (sec)	Toe-Off (sec)
1	0.3	0.432	0.432	0.571
2	0.255	0.335	0.335	0.523
3	0.25	0.375	0.375	0.521
4	0.313	0.654	0.654	0.774
5	0.24	0.582	0.582	0.77
6	0.535	0.784	0.784	0.934
7	0.287	0.407	0.407	0.517
8	0.276	0.396	0.396	0.516
9	0.285	0.412	0.412	0.537
Mean time	0.305	0.486	0.486	0.629
Standard Deviation	0.019	0.033	0.033	0.034

before any other kinematic movements, such as the heel-off and toe-off. We utilized these vertical GRF events to detect step initiations faster. The comparison of the time to detect step initiation between the peak time (proposed) approach and other approaches is shown in Table 3. Our proposed approach was able to detect step initiation faster, in each of the 9 trials, than any other approaches. These findings clearly indicate that the two vertical GRF events can be used to detect step initiations faster than the currently used approaches.

3.3 Prediction of the first step's heel strike time

We derived regression equations for each subject using the two vertical GRF events to predict the first step's heel-strike time as follows;

$$\begin{aligned} \hat{Y}_1 &= 0.6477 - 0.1253x_1 + 1.1018x_2 \\ \hat{Y}_2 &= 1.0166 + 1.0972x_1 - 0.2982x_2 \\ \hat{Y}_3 &= 1.6562 + 0.9637x_1 - 0.2249x_2 \end{aligned} \quad (4)$$

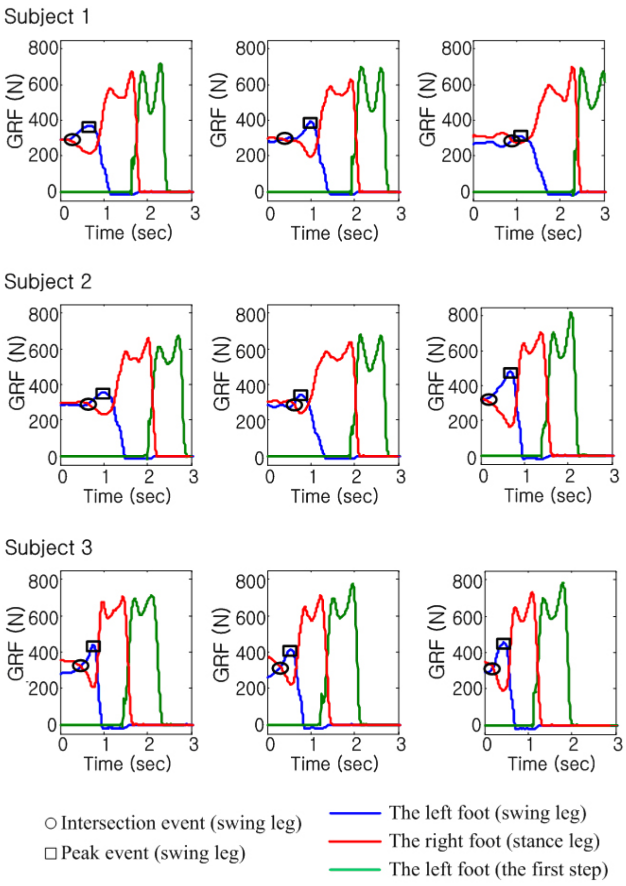

Fig. 4. The vertical GRF patterns for each subject.

Table 4. Comparison between the measured first step's heel-strike time and the predicted first step's heel-strike time.

	Subject 1	Subject 2	Subject 3
Measured	1.250	1.180	1.910
Predicted	1.266	1.188	1.926
Error (%)	1.20	0.67	0.83

where, $\hat{Y}_i$ is the first step's heel-strike time and is dependent upon variables x_1 and x_2. The independent variables x_1 is the first vertical GRF intersection time between the left foot and right foot. The independent variable x_2, is the time of the first peak vertical GRF of the left foot. With the regression equations used in (4), we predicted the first step's heel-strike time and compared it with the measured first step's heel-strike time, which was not used in the regression equation derivation. Table 4 shows the result of this comparison. This analysis indicated that there were no differences in the measured and predicted heel-strike times. These results indicate that vertical GRF events can be used to detect step initiation, and with regression analysis, can also predict the first step's heel-strike time as soon as step initiation is detected.

4. Discussion

The prior approaches used to detect step initiation are the EMG approach, the COP approach, the heel-off approach and the toe-off approach. The EMG approach, which the HAL utilizes, detects step initiation with bio-electrical signals. However, this approach has a few limitations, such as low reliability and long calibration time. The COP approach detects step initiation with the trajectory event of the net COP. However, the COP approach is more suitable for medical therapy and rehabilitation than lower limb exoskeletons. This approach is also suitable for use in a laboratory environment, because reliable COP measurements can be calculated from force plates. The heel-off approach detects step initiation when the heel is lifted just before the front end of the foot leaves the ground. This approach is the latest approach for the lower limb exoskeleton. The RoboKnee utilizes the heel-off approach. However, it is unreliable and requires more kinematic sensors or a complicated control scheme to reliably determine step initiation. The toe-off approach detects step initiation when the toe leaves the ground. This approach is the most reliable, but is slow and requires many sensors as well as a complicated control scheme.

In this study, we utilized GRF events to detect step initiation for the lower limb exoskeleton. We compared the response time for step initiation between GRFs and other kinematic movements. Our results show that the response time of GRFs is the fastest of any movement. This finding enables faster detection of step initiation. Meanwhile, we measured two vertical GRF events using force plates. The first vertical GRF occurred at the intersection between the left foot and the right foot swing, and the vertical GRF of the first step decreased rapidly after the peak value. These GRF events always occurred before a step was initiated. We detected step initiation with the two vertical GRF events and compared the resulting times to other approaches. Our results clearly indicate that the peak time approach is the fastest at detecting step initiation for the lower limb exoskeleton. Additionally, our peak time approach is more reliable and simpler than other approaches, such as the EMG approach, the COP approach, the heel-off approach and the toe-off approach. We were always able to measure the two vertical GRF events for the detection of step initiation. In addition, we were also able to detect step initiation with only the two GRF events faster than any other approaches and without any additional sensors or a complicated control scheme, unlike other approaches. Meanwhile, we predicted the first step's heel-strike time with the two vertical GRF events from the multiple regression equations and compared those predicted times with the measured first step's heel-strike time. Our results indicate that the two vertical GRF events are important and reliable measurements that can detect step initiation faster than other approaches.

5. Conclusion

In this study, we measured and used the two vertical GRF events for the detection of step initiation. This approach enabled us detect step initiation more reliably and faster than other approaches. Our approach can be applied to the lower limb exoskeleton. As a result, it would be possible for the lower limb exoskeleton, which should make it possible for the lower limb exoskeleton to assist the operator's movement faster than currently possible. Most notably, it should lower the operator's metabolic cost, which is the most important factor for evaluating the lower limb exoskeleton. However, it is worth noting that even though our approach was supported through this study, it was not supported with the lower limb exoskeleton. Therefore, future work is necessary to determine whether it reduces the operator's metabolic cost. Additionally, our approach was derived from only three subjects. We will attempt to analyze our approach with a greater number and variety of subjects to ensure reliability.

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