# A Preliminary Study of Ankle Variable Hybrid Above-knee Prostheses

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Abstract: This study is a preliminary study to solve problems in gait imbalance at slope ways and low ramps with ankle variable hybrid above-knee prostheses. For the purpose of implementing ankle variable control, the stance phase in gait was determined as a step-by-step manner and the threshold values were derived through the decision tree learning method based on inertial sensor data in verifying the swing phase. It can be used to perform the ankle variable control. The control of the hybrid above-knee prosthesis was demonstrated by measuring butterfly diagrams on a low ramp for verifying the gait balance in the test ramp.

## 1 INTRODUCTION

Prostheses are an aid used by people who have amputated legs due to natural causes or accidents (Dongfang Xu, et al., 2018). According to a WHO report in 2017, there are an estimated 30 million people who have lower limb amputation disorders, and 60 million people around 2025 throughout the world (WHO, 2018). Therefore, more convenient and more natural functional consideration are being paid to their lost body restoration devices (Steven Culver, et al., 2018; Matthew L. Handford and Manoj Srinivasan, 2018).

Prostheses are divided into two different types, above-knee prostheses and below-knee prostheses, depending on the area of the amputation level. The above-knee prostheses are those used by the amputee below the knee, and the below-knee prostheses are those used by the lower ankle amputee. Due to this location of amputation, the below-knee prosthesis users are generally less uncomfortable with walking by using it than the above knee prosthesis users (Jinying Zhu, et al., 2014; Kyle J. Kaveny, et al., 2018). Therefore, the objective of this study is to develop prostheses with more comfortable and natural functions for the subjects of above-knee prosthesis users who feel pains in their gait.

Recently, the research trend of above-knee prostheses is developing from passive to intelligent type prostheses, and the intelligent type prostheses are divided into powered types, which are directly involved in the movement of the knee joint, and passive types (Elissa D. Ledoux and Michael Goldfarb, 2017; D. Quintero, D. J. Villarreal, D. Lambert, S. Kapp, and R. D. Gregg, 2018). In the case of powered prostheses, it can produce a similar reproduction of a person's gait trajectory because it drives the knee joint using a motor. However, there is a risk that the prostheses may stop while walking due to the limitations of weight and application time of batteries. In order to overcome the limitations, recently, hybrid type prostheses, which combine passive and powered types, are being researched and developed (M. Bellmann, et al., 2010; B. Lawson, et al., 2013; B. E. Lawson, et al., 2014).

The current representative hybrid above-knee prostheses are the MIT Knee and RIC's hybrid knee (T. Lenzi, et al., 2015). The MIT Knee uses motor power only in the swing phase and is powered as a passive type in the stance phase. Unlike the MIT Knee, the RIC's hybrid knee operates in a passive type in the swing phase and uses motor power selectively when optional active force is required in the stance phase. Therefore, although this control method is not a big problem with level walking, it

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causes gait imbalance due to short widths of the affected area caused by passive type prostheses because the bounce trajectory of the knees generated by the initial contact (I.C.) phase, loading response (L.R.), phase, and intermediate stance (M.St., Mid-Stance) phase in the gait of the general stance phase is the same as that of the walkway when entering slopes or on low ramps.

In this study, therefore, the gait imbalance will be compensated by changing the ankle joint for the missing in the knee joint using the below-knee prosthesis, which is implemented by a variable hydraulic cylinder applied to the ankle joint in order to solve the problem.

The method proposed in this study is to attach a variable below-knee with a variable hydraulic cylinder to the above-knee prosthesis that uses power only in the swing phase to give the ankle a flexible change. However, the flexible state of the ankle shall be fixed before the toe-off point at which the foot falls off the ground. This is because the toe-off is the time to gain the gait momentum. Thus, the pressure of the hydraulic cylinder was set to a maximum level before the toe-off by estimating the stance phase of the prosthesis step-by-step.

In order to determine whether this method of gait can solve the imbalance, the butterfly diagrams between the affected and the unaffected sides were measured and evaluated.

# 2 METHOD

## 2.1 Ankle Variable Hybrid Prosthesis

The prostheses used in this study are those that were co-studied with the Korea Orthopedics & Rehabilitation Engineering Center, as shown in Fig.1. The range of motion of the knee joint is 0°～90° and the range of motion of the ankle joint is presented by 16° of planar flexion and 18° of dorsiflexion. The total weight is 4Kg; knee 2.1Kg, ankle 1.4Kg, battery 0.35Kg, and controller 0.15Kg. In the below-knee prosthesis, there is only a motor to control the hydraulic nozzle and no motor for the powered assist function.

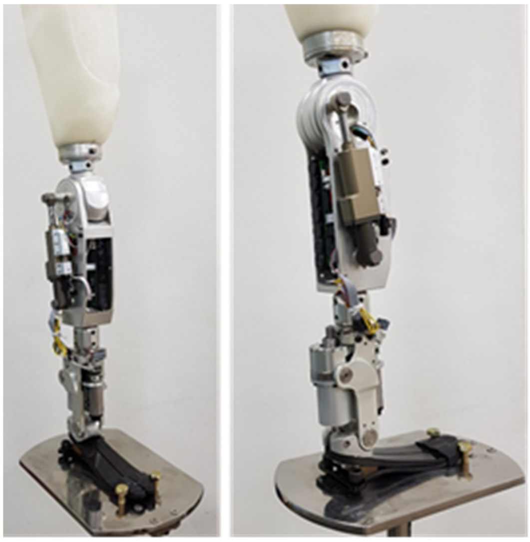

Figure 1: Hybrid above-knee prosthesis of KOREC.

## 2.2 Gait Phase Detection Algorithm

Since the hybrid prosthesis applied in this paper does not have power assist in the stance phase, the gait trajectory in the stance phase resembles the passive prosthesis as shown in Fig. 2. Thus, it is not possible to determine the gait phase based on the gait trajectory. In this study, therefore, the initial contact phase, intermediate stance phase, terminal stance phase, and swing phase were determined by the hip angles, knee angles, progressive angular velocity of the prosthesis, and the angular velocity of the Yaw-axis of gait based on inertial sensors. The threshold values for the determination were derived using an IF ～THEN format based on the decision tree learning method in as shown in Fig. 2. Here, the decision tree learning method was applied to the learner because the sequence of gait is interpreted as the State Machine behavior, which is the specification for the sequential occurrence.

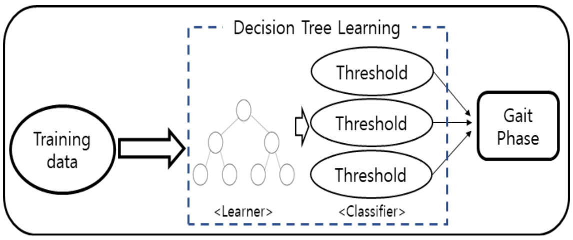


Figure 2: Gait phase detection using a learner.

### 2.2.1 Decision Tree Learning Method

The decision tree learning method is a learner that classifies or predicts dependent variables by changing the rule of decision making into a tree structure as one of the instructional learning that is taught with a label on the training data. It explores the characteristics, patterns, and rules of the target based on structural or unstructured data and analyzes various factors that show relevance. It is possible to see the process of the analysis and is easy to interpret and understand. Also, it has the advantage of being stable and not having to process data. The decision tree learning method is a learner that can be both categorization and regression and can predict both categories and continuous numbers. Recently, a research has been conducted to classify images using the decision tree learning method as well as numerical data (Han Liu, et al., 2017).

$$(\mathrm{x}, \mathrm{Y}) = (x_1, x_2, x_3, \cdots, x_k, Y) \tag{1}$$

The decision tree learning method is represented by Eq. (1) and vector Y consists of labels and vector x, which is a set of input variables $x_1$, $x_2$, $x_3$, and so on.

In the decision tree, the starting node is called a root node and it consists of a branch that connects between the child nodes. The last node that ends the classification is called the terminal node, and the number of branches between the root node and the end node is called depth.

The decision tree learning method proceeds with the separation of data in a way that reduces the impurity as much. The Gini Index, used as an indicator of the impurity, refers to the probability that an item will be randomly selected from a set and then misplaced when estimating a label. The equation for the Gini Index is as shown in Eq. (2).

$$G.I(A) = 1 - \sum_{k=1}^{m} {p_i}^2 \mathrm{w} \tag{2}$$

here, $\mathrm{k} \in 1,2,3, \cdots, \mathrm{m}$ and $p$ is the data in a set labeled i and the Gini Index as a value between 0 and 1.

### 2.3 Hybrid Prosthesis Control

The control of the ankle variable above-knee prosthesis proposed in this study is as follows. The control is largely divided into two stages. The first control is to detect the intermediate stance phase in the stance phase so that the ankle variable can be fixed before the final stance phase in order to obtain gait momentum in the terminal stance phase. The second control is to release the lock on the ankle from the swing phase in order to move the ankle during the initial contact and intermediate stance phases by inertia. Fig. 3 shows this control sequence.

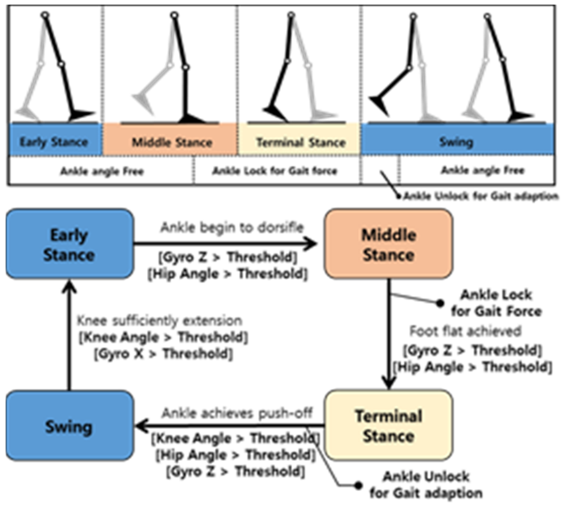


Figure 3: Control block of the ankle variable hybrid prosthesis.

## 3 IMPLEMENTATION AND EVALUATION OF THE PRELIMINARY STUDY

### 3.1 Training and Learning in the Gait Phase

In this study, a decision tree learning method was proposed to determine the gait phase using inertial sensors in the passive prosthesis-based gait. Therefore, to obtain training data for learning, we used the 3R60 prosthesis, Ottobock, to the socket that can be worn by normal people, as shown in Figure 4, in order to obtain training data for learning. Then, a precision small encoder was attached to make certain changes in the joint, together with inertial sensor data. The small rotary encoder was a product of Autonics and the specification is 360 pulses/revolution. The inertial sensor was NGIMU from x-io Technologies and acquired all data through WiFi communication. The reason that we chose the 3R60 prosthesis as a passive type is to fit into the same experimental condition as the user of above-knee prostheses.

The training data were obtained from two healthy 70Kg and three 80Kg men in their 20s, and a passive type above-knee prosthesis user with 72Kg weight on the right side of the Stump Length 44cm.

In the experiment, the gait data was obtained by a total of 500 times with a width of 30cm and five continuous gait steps in which 80% were used as training data, and 20% were used as verification data.

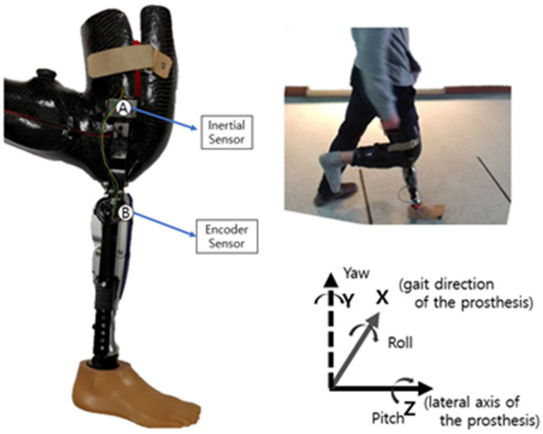


Figure 4: Passive type prosthesis adaptor and sensor attachment locations, experimental setting image and coordinate system used in this experiment.

The values used as an element of the decision tree in the acquired data are the angle of the change in the knee angles obtained by the small encoder, the change in the hip angles of the prosthesis leg acquired by the inertia sensor, the angular velocity of the gait direction of the prosthesis, and the angular velocity of the Yaw axis issued during gait. Fig. 5 represents the acquired data.

In Fig. 5, the knee angle increases sharply at the beginning of the swing phase, and the hip angle increases gradually from the stance phase and begins to decrease at the beginning of the swing phase. The Gyro Z is a Yaw axis movement in the direction of the prosthesis in the swing phase. Data changes on the Yaw axis can be interpreted as a reflection of the amount of movement that occurs when the pelvis moves during gait. Therefore, it is possible to verify that the value of the change is significant in the swing phase.

However, the decision tree was learned with the emphasis on the relation between the knee angle, hip angle, and Gyro Z mentioned previously because the Giro X value, the angular velocity in the gait progress, did not change much of the acquired data.

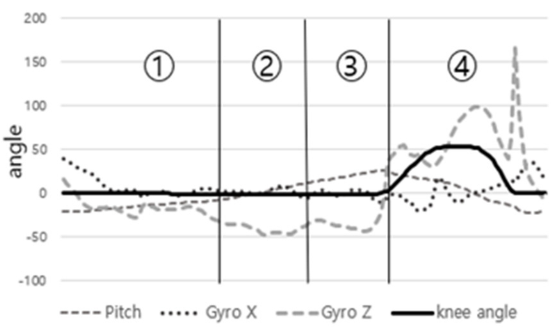


Figure 5: Single gait phase for the machine learning.

### 3.1.1 Evaluation of the Threshold Values Determined by the Decision Tree Learning Method

The threshold values derived from the decision tree learning method performed to identify the gait phase of the passive type prosthesis proposed in this study are shown in Table 1. The threshold values are optimized for the right-side above-knee prosthesis wearer for the final evaluation in this study.

For the evaluation of the derived threshold values, an evaluation program was produced as shown in Fig. 6 and a simulation was performed by applying 20% of the acquired data randomly. As a result, the accuracy of 98.6% of the initial contact phase, 97.2% of the intermediate stance phase, 98.9% of the terminal stance phase, and 99.8% of the swing phase was derived. Also, the trigger signal to release the lock on the ankle was 99% accuracy

In addition, it showed that there is room for improving the accuracy of the trigger signal because the trigger signal for setting the lock on the ankle was detected with an average of 97.2% accuracy.

Table 1: Threshold values of the gait phase derived from the learning.

| Phases | Boundary Value |
|---|---|
| Initial Contact | Gyro Z < -10.392, Hip angle < 1.09251, Knee angle <= 0.432182, and the other three thresholds |
| Mid Stance | Gyro Z < -10.392, Hip angle >= 1.09251, Hip angle < -11.2027, and the other one threshold |
| Terminal Stance | Gyro Z < -10.392, Hip angle >= 1.09251, Hip angle < -11.2027, and Gyro X >= 7.72385 |
| Swing | Gyro Z >= -10.392, Knee angle >= 1.09251, Hip angle >= -3.47349, and the other three thresholds |

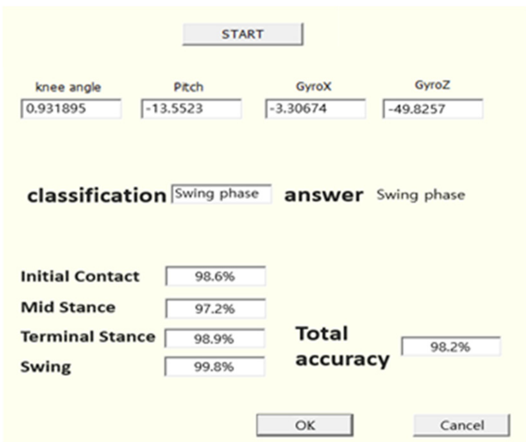


Figure 6: Evaluation program of the learner.

### 3.2 Evaluation of the Gait Balance in the Ankle Variable Control

An experiment that determines whether the variable control was properly performed was implemented in order to evaluate the gait balance as the ankle variable control was applied based on the gait phase of the classified stance phase. The experiment confirmed the change of the ankle with a three-dimensional motion analyzer based on the control trigger signal from the classifier. A three-dimensional motion analysis system (Cortex 6.02, Motion Analysis Corp., USA) was used to confirm the results. The system consists of 12 infrared cameras, with 120 Hz of sampling and 12.5Cm diameter reflective markers. The experiment for the evaluation measured changes in the ankle by attaching markers on both ankles.

In the first experiment, the angle changes of the planar flexion and dorsiflexion of the ankle were observed. The measured graph is shown in Fig. 7. It was confirmed that proper changes in the ankle alone represent gait trajectories, which are similar to the actual healthy angle. Thus, it has been confirmed that the ankle variable control can help the gait balance of the above-knee prosthesis users.

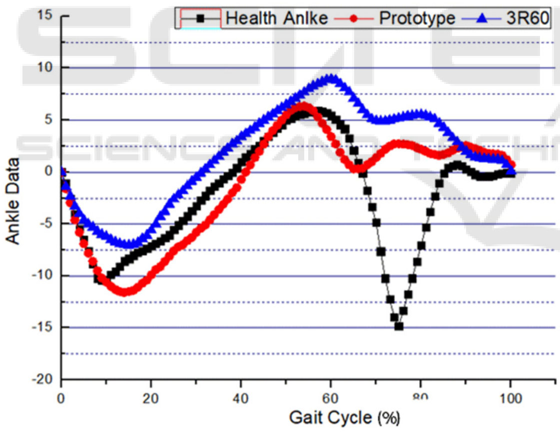


Figure 7: Gait trajectory of Helthy Ankle, Variable (Non-Powered) Ankle and Fixed Ankle.

In the second experiment, seen the differences of unaffected stride in general ankles fixed type prosthesis whether can be solved. The experiment utilizes a load cell sensor mounted on the prosthesis. The load cell is tied to the joint of the transfemoral prosthesis and lower limb prosthesis. The experiment was conducted under three conditions: the ankle was fixed from the beginning, the variable state from the swing phase to the intermediate stance phase and fixed after the intermediate stance phase, and the variable conditions between all gait cycles. The results are presented in Fig. 8.

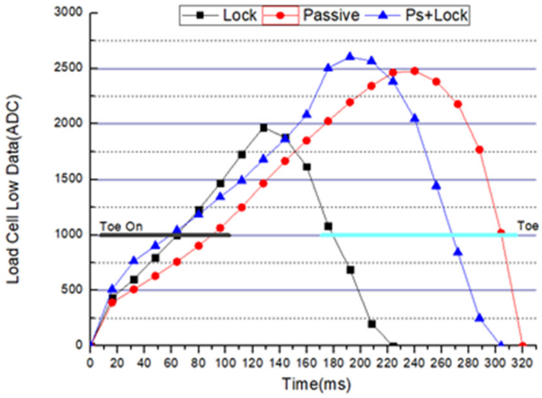


Figure 8: Gait stance according to the Variation of Ankle Control.

When walking with the ankle in a fixed state, the toe off point tends to be shortened, and in contrast, the toe off point could be confirmed to be longer if the ankle is set as a flexible state. Therefore, it has been confirmed that the appropriate toe off timing can help with gait balance.

Finally, the dynamic foot pressure examination was checked to verify the actual gait balance between the affected and the unaffected sides. The evaluation was implemented using the Gait analysis treadmill from Zebris. The gait speed was 1.5km/h, and the gradient was 4°. In the evaluation method, the reason for the low slope rather than level ground is the arbitrary setting for measuring the gait imbalance on the ramp entry section as a problem mentioned in the introduction. Fig. 9 shows the evaluation graph. As shown in Fig. 9, it was verified that the ankle variable hybrid prosthesis proposed in this study represents the gait balance in comparison to the 3R80 passive type above-knee prosthesis with the clearly fixed ankle.

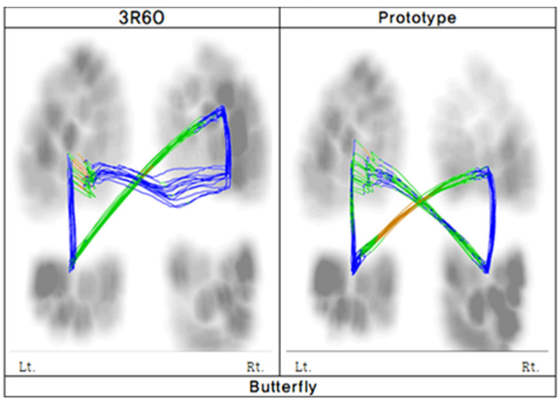


Figure 9: Butterfly diagram of Existing prosthesis and Prosthesis with proposed techniques.

This is because proper changes in the ankle joint during gait have partially compensated for the bounce role of the load reactor in the stance phase gait trajectory in the gait of normal people. Also, it can be attributed to the fact that the swing phase assisted power to the movement of the knee joint.

## 4 CONCLUSIONS

In this study, a preliminary study was performed to solve the gait imbalance of passive type prostheses that occur on the entrance or low slope of the ramp, through applying the ankle variable hybrid prosthesis developed by the Korea Orthopedics & Rehabilitation Engineering Center. As a result of the performance, it was confirmed that only the variation in the ankle showed the gait balance. The results confirmed that even though the powered below-knee prosthesis was not used, the gait balance was achieved in the hybrid above-knee prosthesis. Thus, it has been confirmed that this gait control can improve the convenience of the users of above-knee prostheses. However, this is the early stage of the study and is a lack of suggestion of quantitative ankle joint resistances. Also, it still requires further experimentations in a gait environment with high slopes.

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