A STUDY ON THE CORRELATION BETWEEN THE FOOT FEATURES AND GAIT CHARACTERISTICS DURING OVER-GROUND WALKING

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We analysed the correlation between the foot features such as foot length, foot width, the height and angles of foot arch curves and gait spatiotemporal parameters. To measure the structure of the foot, we measured the height and structural variation of medial longitudinal arch(MLA) and lateral longitudinal arch(LLA) in various conditions using a ‘ Scanning stage’ consisting of a single depth camera and four uni-axial force sensors. The gait spatiotemporal parameters were obtained by a motion capture system from the seventeen subjects. All subjects were instructed to walk at a regular pace, and spatiotemporal gait parameters of ten strides in the middle of the walkway were measured. As a result, it has been shown that the height angle of MLA is significantly correlated with gait temporal parameters while the LLA is significantly related to gait spatial parameters.

KEY WORDS: foot features, foot-arch, scanning stage, gait features, spatiotemporal gait parameters

INTRODUCTION: Customized sports gears refer to equipment designed to be optimized for various body parts of a particular individual to maximize the athletic performance and functionality and to prevent potential injuries that may occur during exercises. Recently, the development of such customized sports gears is actively underway.
The foot is a first body part that touches the ground directly, and plays a key role in contributing to a postural control and providing forward propulsion during exercise (Stolwijk, 2014; Hayot & Sakka, 2013; Lin, 2014). Given the important role of the foot, it is possible to improve the performance of sports activities by enhancing the functionality of the foot through the customized insole. The customized insole can be manufactured by considering the foot features, and it can contribute to weight bearing, shock absorption, propulsion and postural control by supporting the foot arches which are consisted of medical longitudinal arch (MLA), lateral longitudinal arch (LLA), and transverse arch (Chang, 2014; Wright, 2012; Fukano & Fukubayashi, 2009). However, there are still many limitations of the foot feature measurement method for the fabrication of current customized insole. First, the measurement was performed only in a static posture. Second, it did not consider association between measured foot characteristics and movement characteristics such as walking and running. Last but not least, although the LLA of the foot arch is closely related to the lateral side stress fracture, the characteristics of the LLA were not analysed (Fukano & Fukubayashi, 2009).
Therefore, the aim of this study is to analyse the correlation between the foot features such as MLA and LLA measured in both static and dynamic conditions and the gait features which represents the basic athletic ability. It is expected that the results of this study will be ultimately used to fabricate three dimensional personalized insole design.

METHODS: Overall system for the experiments consists of a scanning stage for measuring foot features and an inertial measurement unit (IMU) sensors for obtaining gait characteristics.

1) The foot feature measurement system (Scanning stage)

A foot feature measurement system (FFMS) is composed of a measurement system and analysis modules. The measurement system comprises a runway and a scanning stage (Fig. 1). The runway is a wooden structure of 200 cm (length) × 70 cm (width) × 45 cm (height), and the scanning stage is composed of a single depth camera (Intel Realsense F200) embedded underneath the transparent acrylic panel and four uniaxial force sensors at the corners of the panel. The built-in depth camera is based on three-dimensional (3D) point cloud data and used to measure the morphological characteristics of the foot and the geometric structure of the foot arch, whereas the force sensors are set up to investigate the stability of movements based on the center of pressure (CoP) of the body (Fig. 1). All obtained images and CoP data were timely synchronized and stored in an in-house developed software. The analysis module can be used to analyse the geometric structure and CoP trajectory based on the obtained data, thereby allowing to extract foot feature parameters such as foot length, foot width, and height and area of the MLA and LLA curves from the images obtained with the FFMS in three conditions; 1) sitting, 2) standing, and 3) One-leg standing (OLS).
To obtain the curves of the MLA and LLA, we defined the MLA line as the line from the calcaneus bone to the first MTP joint, and the LLA line as the line from calcaneus to the fourth MTP joint. We defined MLA and LLA curves by projecting MLA and LLA lines onto the plantar surface of the foot. The height of MLA was defined by the apex of the MLA curve. From the triangle connecting the MLA line and the apex of the MLA curve, we calculated MLA height angle which is defined as the subtended angle between the line from the calcaneus bone to the apex of the MLA and the line from the apex of MLA curve to the first MTP joint. The LLA curve was adjusted in the same manner (Fig. 1).

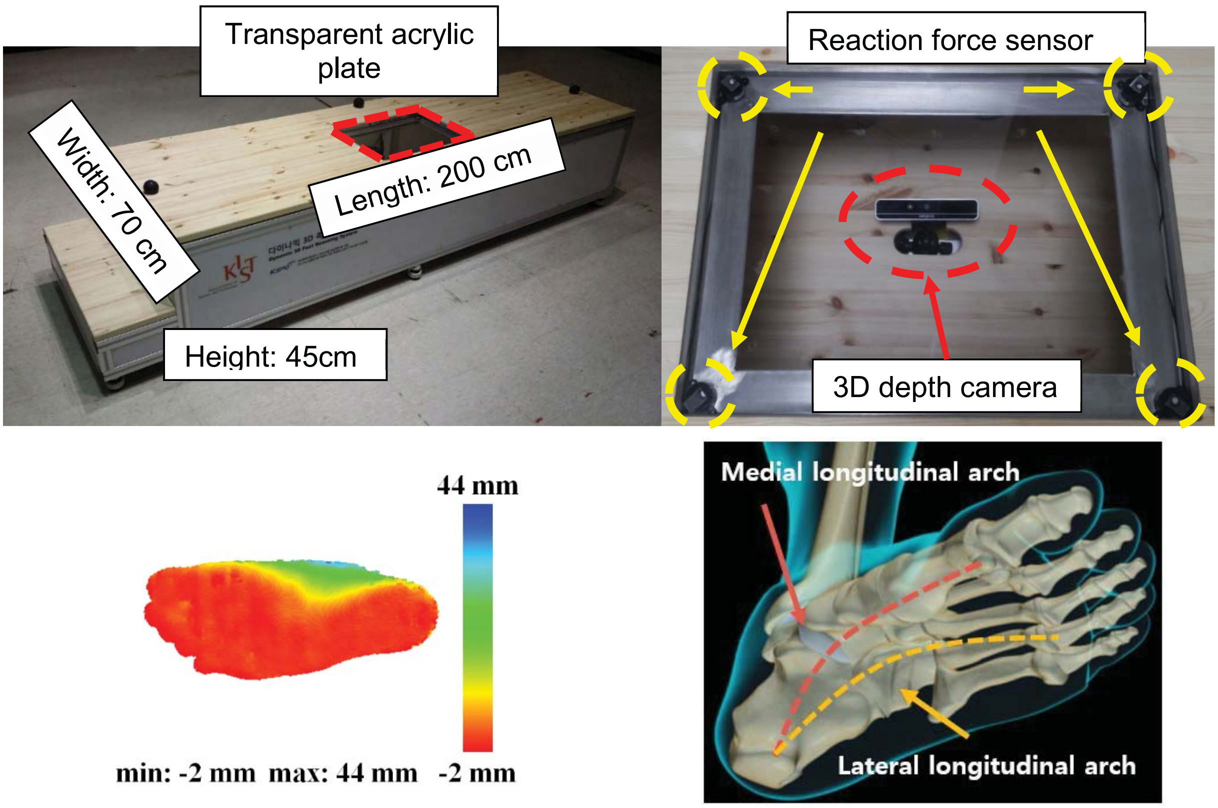

Figure 1: The structure of foot feature measurement system (scanning stage), the obtained depth image, and the extraction of MLA and LLA curves.

2) Gait feature measurement system
Gait features were measured using commercialized gait analysis equipment (Xsens MVN, Netherlands) which consists of seven IMU sensors (Fig. 2). The gait feature measurement

system was attached on a subject's lower limb and calculated gait kinematic parameters as well as gait event information such as heel strike and toe-off times.

(a) (b) (c)

Figure 2: a) the gait feature measurement system (Xsense MVN), b) actual gait experiment, and c) software of the gait feature measurement system

The gait experiment was performed while the subjects were walking on 25 meters even ground with their preferred speed. Ten strides in the middle of the walkway except unstable stride at the first and end five meter were used for the analysis. The gait spatiotemporal parameters such as stride length, step length, gait velocity, single limb support (SLS) time, double limb support (DLS) time, and percent of stance phase were extracted from the system.

3) Statistical Analysis

All the foot feature and gait feature were obtained from seventeen healthy young subjects (age: 29.4 ± 5.06, height: 174.94 ± 4.87, and weight: 73.35 ± 7.98). For statistical analysis, the Pearson-correlation coefficient was calculated between the foot feature parameters and gait spatiotemporal parameters by using SPSS software (SPSS, Chicago, IL, USA). The correlation coefficient, r, shows the level of correlation, and is classified as very high, high, moderate, low, and very low at 0.9–1, 0.7–0.9, 0.5–0.7, 0.3–0.5, and 0.1–0.3, respectively. The significance level was set to $p < 0.05$.

RESULTS: Table 1 and 2 show the correlation coefficients and the significant level between selected foot and gait features. The results showed that the MLA height angle in OLS condition had negative moderate correlation with stride time, step time, stance time and % of stance phase which are the gait temporal parameters (Table 1). In addition, the height angle of LLA in OLS condition were significantly correlated to the stride length, step length, and gait velocity which are the gait spatial parameters (Table s)

Table 1
The correlation between MLA height angle and stride time, step time, stance time, and % of stance phase

		Stride time	Step time	stance time	% of stance phase
MLA height angle in stand condition	*r*	-.318	**-.504**	**-.492**	**-.602**
	p	.214	**.039**	**.045**	**.011**
MLA height	*r*	**-.475**	**-.623**	**-.612**	**-.488**

angle in OLS condition	*p*	**.050**	**.008**	**.009**	**.047**

Table 2
The correlation between LLA height angle and stride length, step length, and gait velocity

		Stride length	Step length	Gait velocity
LLA height angle in stand condition	*r*	-.271	.223	.313
	p	.292	.390	.220
LLA height angle in OLS condition	*r*	**.605**	**.617**	**.610**
	p	**.010**	**.008**	**.009**

DISCUSSION: The significant correlation were found between the foot feature parameters extracted from the scanning stage and the gait feature parameters extracted from the commercialized IMU sensor system. From the results, it can be known that as the MLA height angle in OLS condition increases, the stride time, step time, stance time, percent of stance phase were decreased but no correlation with swing time. It can be explained that the subjects with wider MLA angle tend to have shorter duration of one limb staying on the ground, thus the MLA may be associated to the gait temporal parameter management. In addition, it was shown that as the LLA height angle in OLS condition increases, the stride length, step length, and gait velocity also increase. It means the wider the LLA arch curve, the longer and faster stride length and gait velocity will appear. Therefore, it can be concluded that the LLA structure may be associated to the gait spatial parameter management. From the findings obtained from this study, it can be concluded that the MLA modulates the gait temporal parameters while LLA tunes the gait spatial parameters. Despite the significant findings of this study, we could not consider the association between foot parameters and gait spatiotemporal parameters in terms of various arch types or subjects with different ages.

CONCLUSION: This study analysed the association between foot features and the gait spatiotemporal parameters in order to obtain more advanced data for use in the personalized insole design. We found that MLA was related to the gait temporal characteristics, while the LLA was significantly related to the gait spatial characteristics. This is the first study showing the association and importance of the foot arches to the gait modulation. It can be expected that the results of this study will be used as a basic data for customized insole design parameters. In the future, we will extend this study for patients with structural abnormalities in their foot.

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Acknowledgement
This research project was supported by the Sports Promotion Fund of Seoul Olympic Sports Promotion Foundation from Ministry of Culture, Sports and Tourism.