# VALIDITY OF A FBG-BASED SMART SOCK SYSTEM FOR MEASURING TOE GRIP FUNCTION IN HUMAN FOOT

YIXUAN LEOW
School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798.
email: YLEOW005@e.ntu.edu.sg

MARABELLE LI-WEN HENG
Podiatry Department, Diabetes & Metabolism Centre, 17 Third Hospital Drive, Singapore General Hospital, Singapore 168752
Email: marabelle.heng.l.w@sgh.com.sg

YIMIN LIU
School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore 639798.
email: liuyiminjl@163.com

DANIEL TIK-PUI FONG
National Centre for Sport and Exercise Medicine, School of Sport, Exercise and Health Sciences, Loughborough University, United Kingdom.
Email: D.T.Fong@lboro.ac.uk

CHI CHIU CHAN
Sino-German College of Intelligent Manufacturing, Shenzhen Technology University, China
Email: ccchan@sztu.edu.cn

PUI WAH KONG[††]
(Corresponding author)
Physical Education and Sports Science Academic Group, National Institute of Education, Nanyang Technological University, 1 Nanyang Walk, Singapore 637616.
Email: puiwah.kong@nie.edu.sg

This study developed a smart sock system using optical fiber technology to measure the toe grip function of individual toes. The system comprised Fiber Bragg grating (FBG) sensors incorporated into a sock garment for measuring maximum toe flexion displacements. Calibration equation of each FBG sensor was determined from 3D motion capture system on 10 female subjects. The validity of the smart sock system was checked by comparing maximum toe flexion displacement against the gold standard of 3D motion capture. The root mean squared error was 0.95 (0.57) cm across 10 toes. The magnitude of toe displacement and error were similar between the left and right foot. In conclusion, the FBG-based smart sock system can successfully measure maximum toe flexion displacements of individual toes simultaneously. This system can be developed to support the evaluation of toe grip function in clinical and field settings.

Keywords: Fiber Bragg grating; optical fiber; displacement; foot; toes

## 1. Introduction

Toe grip function of a human foot plays an important role in postural and movement control. Inadequate toe grip strength is associated with foot disorders such as hallux valgus or lesser toe deformities[1,2]. It has been shown that toe grip strength decreases with ageing[3] and that poor toe grip function is related to reduced balancing ability[4] and increased risk of falls among older adults.[2] In athletes, strength training of the toe flexor muscles contributes to enhancing jump performance.[5] Thus, the evaluation of toe grip function has its applications across different populations and age groups.

At present, there are no standard methods to measure toe grip function. Clinicians have used a paper grip test to evaluate the function of the first toe but this test is unreliable.[6] A textile crunching test has been used in children whereby subjects were asked to crunch a 60-cm textile via toe flexion in the shortest possible time.[7] This test, however, is highly dependent on the textile material and the floor surface and therefore not easy to be standardised. A custom-made dynamometer has been developed to determine the maximum voluntary isometric contraction of toe flexor muscles for laboratory experiments.[5] A toe grip dynamometer (Takei Scientific Instruments Co., Japan) was designed for field tests and clinical use, though the device cannot accommodate individuals with short toes and foot deformities.[3,8] All previous methods assess the grip function of either the first toe only[6] or all 5 toes together as a whole.[3,5,7,8] To the authors' best knowledge, there is no existing instrument that independently evaluate each of the 5 toes of the foot. Such knowledge may be useful in monitoring the function of each toe and identifying specific locations of any foot disorders.

To comprehensively evaluate toe grip function of the human foot, this study aimed to develop and validate a smart sock system for measuring toe grip function of individual toes.

## 2. Methods

### 2.1 *Development of the Smart Sock System*

We propose a light-weight smart sock system that can simultaneously evaluate the grip function of each of the 5 toes in a human foot using optical fiber technology. Fiber Bragg grating (FBG) is a type of distributed Bragg reflector constructed in a short segment of optical fiber (Figure 1). FBG reflects particular wavelengths of light and transmits all others by creating a periodic variation in the refractive index of the fiber core, which in turn generates a wavelength-specific dielectric mirror.[9] FBG can therefore be used as an inline optical filter to block certain wavelengths, in other words, as a wavelength-specific reflector.

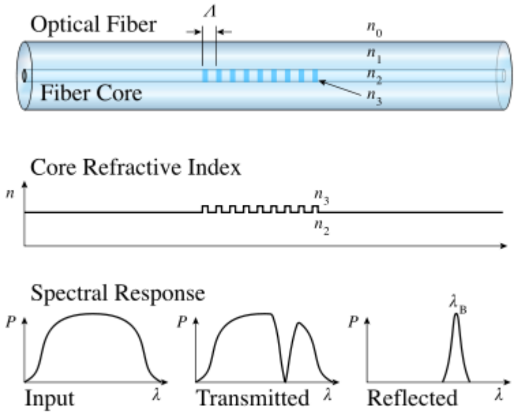


Figure 1: A Fiber Bragg grating (FBG) structure, with refractive index profile and spectral response.

In order to achieve FBG backscattering for detection, the central wavelength of the reflected component must satisfy the Bragg condition:

$$\lambda_{ref} = 2n\Lambda$$

where n is the index of refraction and $\Lambda$ is the period of the index of refraction variation of FBG. Since the parameters n and $\Lambda$ exhibit a strong strain dependency when a force is exerted along fiber axis, the Bragg wavelength $\lambda_{ref}$ of the reflected component is modulated as a function of strain.

In the proposed smart sock system, a pair of 5-toe sock garments were used. In each sock, 5 FBGs with different Bragg reflection wavelengths ($\lambda_1$ to $\lambda_5$) are fixed on the top surface of the sock near the toes area (Figure 2). The FBG grid is located about 1 cm distal to the metatarsophalangeal joint. Since the sensing area is not close to the measuring point and the connected single-mode fiber is easily extended, the smart sock system can accommodate different toe lengths and shapes. The working principles of the smart sock system is described as follow: 1) The light from the light source is transmitted to a 1 × 5 optical fiber coupler through an optical fiber circulator; 2) FBGs reflected the specific wavelengths pass through the coupler back into the port b of the optical fiber circulator, then transmitted to the FBG interrogator, and 3) After demodulation, the spectrum of five different Bragg reflection peaks is displayed on the computer.

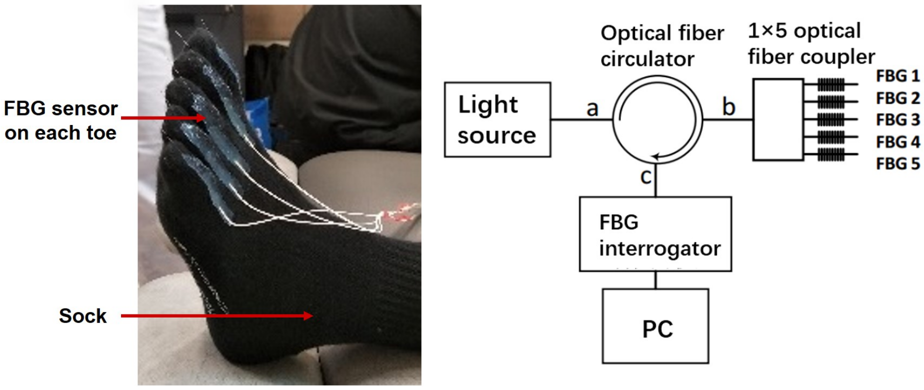


Figure 2. Physical and schematic diagram of the smart sock system with fiber Bragg grating (FBG) sensors for measuring toe grip function of individual toes.

In the measurement process, a wooden triangular wooden stand was used to support and maintain the ankle in a neutral position (Figure 3). As the toes flex from the neutral start position to maximum flexion, a strain acts on each of the FBG, causing the Bragg reflection peak to drift. The wavelength ($\lambda_{1\text{-}X}$) is the reflection peak of the wavelength ($\lambda_X$) after the drift, and the amount of wavelength drift can be calculated as $\Delta\lambda = \lambda_{1\text{-}X} - \lambda_X$. By demodulating the wavelength drift, the toe grip displacement can be evaluated.

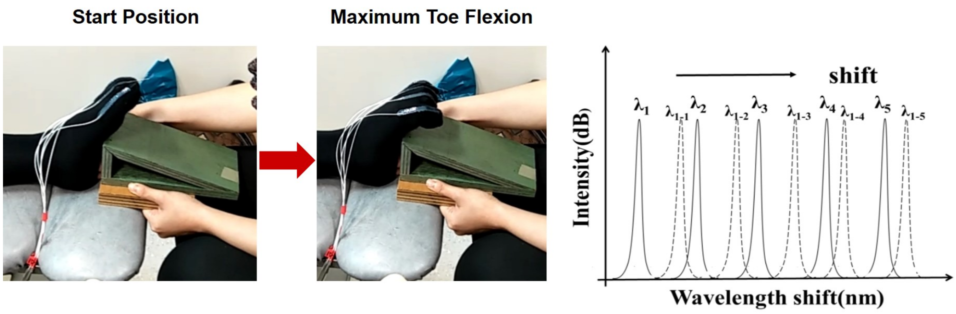


Figure 3. Toe displacement by gripping motion can cause Bragg reflection peak to drift.

**2.2 *Calibration***

The calibration experiment was approved by the Nanyang Technological University Institutional Review Board (IRB-2016-11-032). To obtain calibration equations for the FBG sensors in the smart sock system, 10 female subjects with no known foot conditions were recruited. The inclusion criteria of the subjects were: 1) aged 21 to 45 years, 2) free from any foot injury at the time of the study, 3) no injuries in the foot that resulted in a rest period of seven days or more during the last six months, 4) no history of foot surgery, and 5) not have any rheumatological or connective tissue conditions. Subjects were excluded if they had gone through any surgeries to the foot, had serious foot injuries, experienced discomfort or pain of the foot at the time of the study, or self-reported any foot deformities (e.g. bunions). All subjects provided written informed consent to participate in the study.

The calibration procedures were carried out in a laboratory using a three-dimensional (3D) motion capture system with four infrared cameras (Vicon, Oxford, UK) as the gold standard of measuring toe flexion displacement. Before wearing the smart sock system developed in the present study, each subject first put on a pair of thin disposable stocking for hygiene reasons. During the test, the subject laid in a supine position on an examination table with the legs extended in a comfortable position. The ankle is held in neutral by the wooden stand. At the tip of each of the 5 toes, a retro-reflective marker was adhered of the smart sock garment to allow motion tracking of the toe flexion movement using the 3D motion capture system (Vicon, Oxford, UK).

The calibration experiment was conducted following the procedures of a previous study using FBG sensor to measure the first toe movement.[10] The toes flexed and paused at four intervals from the neutral starting position to maximum toe flexion. Each interval was held stationary for several seconds so that stable wavelength drift of the FBGs could be recorded. As the toes moved, the displacement was concurrently recorded by the smart sock system and the 3D motion capture system. By fitting a linear line to the data obtained from both systems, the relationship between the wavelength drift and the toe displacement of each FBG sensor can be determined. To determine a relationship that can be generally applied to other subjects rather than limiting to one's own data, dataset from all 10 subjects were combined to get a calibration equation for each of the 10 toes (5 left, 5 right). With these calibration equations, future toe displacement can be measured directly from Bragg reflection peak drift read from the FBG demodulator without the need of any 3D motion capture system.

### 2.3 *Validation*

To verify the accuracy of the calibration equations, independent datasets of maximum toe grip displacement were obtained from all 10 subjects. This process allows the values calculated from the FBG calibration equations to be checked against those measured from 3D motion analysis. In this validation experiment, subjects were asked to flex all the toes at once to maximum range and hold for 3 seconds. The wavelength drift data of the smart sock system were substituted into the FBG calibration equations to calculate maximum toe grip displacement. The toe movement was concurrently captured using the 3D motion analysis system as the gold standard. Root mean squared (RMS) errors of the toe grip displacement measured from the smart sock system were computed against the gold standard to check for validity. For each subject, nine independent trials were taken and the average RMS error value was used for each toe.

## 3. Results

The maximum toe flexion displacements captured by 3D motion capture were similar between the left and right foot, with the 2$^{nd}$ toe flexed the most and the 5$^{th}$ toe flexed the least (Figure 4). When compared with the 3D motion capture as gold standard, the RMS error of the smart sock system was 0.95 (0.57) cm on average (Table 1).

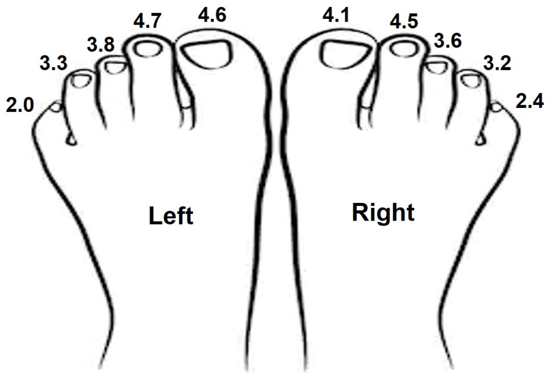


Figure 4. Maximum toe flexion displacement (cm) of 10 individual toes measured using Vicon 3D motion capture system.

Table 1. Root Mean Squared (RMS) Error of the Smart Sock System compared with Vicon 3D Motion Capture in Measuring Maximum Toe Flexion Displacement

| | Left foot (cm) | | Right foot (cm) | |
|---|---|---|---|---|
| Toes | Vicon | RMS error | Vicon | RMS error |
| 1st | 4.61 (1.11) | 1.11 (0.78) | 4.07 (1.22) | 0.92 (0.48) |
| 2nd | 4.66 (1.18) | 0.97 (0.50) | 4.47 (1.09) | 0.98 (0.62) |
| 3rd | 3.81 (0.56) | 1.30 (0.56) | 3.62 (1.14) | 1.21 (0.82) |
| 4th | 3.26 (1.05) | 0.88 (0.50) | 3.24 (1.14) | 0.97 (0.65) |
| 5th | 2.00 (0.84) | 0.54 (0.24) | 2.35 (1.26) | 0.63 (0.56) |
| Mean (SD) | 3.67 (0.95) | 0.96 (0.52) | 3.55 (1.17) | 0.95 (0.63) |

Data are expressed as mean (standard deviation).

## 4. Discussion

This study developed a smart sock system using FBG sensors to simultaneously measure toe grip function of individual toes. The system was calibrated and validated against the gold standard of 3D motion capture. On average, the measurement error was less than 1 cm across all 10 toes.

At present, all existing methods for the evaluation of toe grip function have limitations. For example, the paper grip test is subjective and only assess the first toe.[6] The textile crunching test and toe grip dynamometer assess the overall function of all five toes of a foot as a whole without separating the contribution of each toe.[3,7,8] In previous studies which used a toe grip dynamometer to measure toe flexion strength, some toes such as the 4th and 5th toes may be too short to reach the grip bar and hence being neglected during the test.[3,8] The smart sock system developed in the present study overcome some of these limitations as it can measure all five toes of a foot simultaneously. At the same time, it allows the testers to monitor each toe independently. The smart sock system can also accommodate toes of different lengths and shapes, offering a more flexible solution to a grip bar with fixed dimensions.[3,8] This is an important consideration as foot deformities such as hallux valgus (bunions) are quite common, especially among women.[11] In community-dwelling older adults, decreased toe flexor strength was associated with slower walking speed, shorter periods of single-limb support phase, and shorter stride length during walking. These findings support that toe flexor muscles play an important role of toe flexor muscles in walking.[12] It should noted that the present study measured toe flexion displacements which are kinematic parameters without consideration of forces. During human gait, it is important to also consider kinetic parameters which power the plantar flexion of the toes.[13]

Findings from our study showed that the 2nd toe moved the largest range and the 5th toe moved the least; this pattern was consistent in both left and right feet (Figure 4). The big toe ranked second in terms of maximum displacement; on the left foot there was only a 0.1-cm (2%) difference between the big toe displacement (4.6 cm) compared to the largest displacement reported (4.7 cm). The function of toes, in particular the maximum toe flexion displacement (which reflects the joint range of motion) may potentially be useful in providing insight and the evaluation of falls risk. In elderly aged above 60 yrs, it is reported that joint range of motion, particularly the ankle joint is associated with people who had two or more falls in a year[14]. In future, it would be beneficial also to examine the toe joint range of motion and its association with falls risk.

The measurement error of the smart sock system was overall less than 1.0 cm across all 10 toes when compared with the gold standard of motion capture. There were a few potential sources of error. First, the calibration equation of each toe was obtained using data from all 10 subjects rather than specific to one subject. The rationale was to obtain a general calibration equation that can be applied to any subjects in future tests. While this method simplifies the procedures, the accuracy of the calibration is likely compromised compared with subject-specific calibration. Second, other parts of the foot such as the ankle joint may have inevitable flexed slightly when subjects flexed their toes during the experiment. These unwanted foot movements would have affected the 3D motion capture data of toe flexion displacement. To minimize foot movements other than toe flexion, we used a wooden stand to secure the ankle neutral position on the plantar foot from heel metatarsophalangeal joints (Figure 3). Collectively, there is room to further improve the calibration procedures and accuracy of the smart sock system.

There are some limitations to the present study. Firstly, the calibration equations and validation experiment of the smart sock system were performed only on female subjects since only one prototype was made. Given the difference in anatomical structure and function between males and females, there is a need to include male subjects in the future studies. Secondly, the sock prototype at the current stage is rather fragile and needs to be handled with care. Thus, it is time consuming when the subjects wear and remove the sock gently with care. For practical use in a clinical setting, future development should aim towards a cable-free and durable system that can be attached and removed from patients easily. Thirdly, this system only measures displacement and does not measure force outputs by the toe joints. A future combination assessment for displacement and force will give more useful readings for toe joint function. Finally, offline data processing is still needed when using the current smart sock prototype. Future optimization of software is required to generate immediate results and to make the system more user-friendly and straight forwards for potential users such as trainers, clinicians and therapists.

## 5. Conclusion

This study developed a FBG-based smart sock system can successfully measure maximum toe flexion displacements of individual toes simultaneously. This system can be further improved to support the evaluation of toe grip function in clinical and field settings.


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## Disclosure statement

There are no potential conflicts of interest.

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