THE VALIDITY AND RELIABILITY OF TRUEDEPTH CAMERA EMBEDDED IN THE PHONE FOR FOOT MEASUREMENT

Qian LU[1], Shunxun LI[1], Jin ZHOU[1*], Zhifeng YAO[2], Wei LI[2]

[1]Sichuan University, College of Biomass Science and Engineering, National Engineering Laboratory for Clean Technology of Leather Manufacture, Section of Chengdu No. 24 Southern Yihuan, 610065, Chengdu, China, zj_scu@scu.edu.cn

[2]Beijing Luxcreo, Inc., Beijing, P.R. China

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ABSTRACT. There are several laser or structured-light based foot scanners available on the market, which can be used to obtain accurate 3D foot models. Compared to those 3D scanning devices, TrueDepth cameras are portable, inexpensive and easy-to-use. However, the accuracy and reliability of their 3D foot scanning remain to be confirmed. This study aimed to verify the validity and reliability of structured light TrueDepth camera integrated into the mobile phone when it is used for foot measurement. Thirteen students without any kinds of foot abnormalities or foot diseases were recruited and their feet were measured by both Infoot 3D foot scanner and mobile phone with TrueDepth camera. Three parameters were measured including foot length, foot breadth and ball girth. Subsequently, the reliability and validity of the two methods were assessed by linear regression analyses, intraclass Correlation Coefficient and Bland-Altman analysis. The foot breadth and girth circumference measurements all showed high coefficients of determination (R^2>0.8) between the two methods and three measurements indicated good to excellent agreements (ICCs>0.9), although the length measurement was reported without significant coefficients of determination. Further, findings from Bland-Altman analysis demonstrated that the measurements from the TrueDepth camera had good agreements with those from Infoot and they could be used interchangeably. However, with the reconstruction algorithm updating in the near future, we could foresee the promotion in foot length measurement when using the TrueDepth camera from the phone. The TrueDepth camera utilizing structured-light and the customized application for foot measurement has fast, accurate and low-cost features and it is a convenient and economical method to obtain the foot 3D model. It can be widely applied for medical purposes and customization.

KEY WORDS: foot measurement, foot 3D model, structured-light, TrueDepth camera

VALIDITATEA ȘI FIABILITATEA CAMEREI TRUEDEPTH ÎNCORPORATE ÎN TELEFON UTILIZATE LA MĂSURAREA PICIORULUI

REZUMAT. Există mai multe scanere pe bază de laser sau cu lumină structurată disponibile pe piață, care pot fi utilizate pentru a obține modele 3D exacte ale piciorului. În comparație cu acele dispozitive de scanare 3D, camerele TrueDepth sunt portabile, ieftine și ușor de utilizat. Cu toate acestea, acuratețea și fiabilitatea acestora în cazul scanării 3D a piciorului trebuie confirmate. Acest studiu și-a propus să verifice validitatea și fiabilitatea camerei TrueDepth cu lumină structurată integrată în telefonul mobil atunci când este utilizată la măsurarea piciorului. S-au recrutat treisprezece studenți fără niciun fel de anomalii ale piciorului sau boli ale piciorului, iar picioarele acestora au fost măsurate atât cu ajutorul unui scaner 3D pentru picior, cât și cu un telefon mobil cu cameră TrueDepth. S-au măsurat trei parametri, și anume lungimea piciorului, lățimea piciorului și circumferința zonei metatarso-falangiene. Ulterior, fiabilitatea și validitatea celor două metode au fost evaluate prin analize de regresie liniară, coeficient de corelație intraclasă și analiză Bland-Altman. Măsurătorile lățimii și circumferinței piciorului au indicat coeficienți mari de determinare (R^2>0,8) între cele două metode și trei măsurători au indicat acorduri bune spre excelente (ICCs>0,9), deși măsurarea lungimii a fost raportată fără coeficienți de determinare semnificativi. Mai mult, descoperirile în urma analizei Bland-Altman au demonstrat că măsurătorile luate utilizând camera TrueDepth au avut acorduri bune cu cele luate cu scanerul Infoot și pot fi folosite interschimbabil. Cu toate acestea, odată cu actualizarea algoritmului de reconstrucție în viitorul apropiat, am putea prevedea progresul în măsurarea lungimii piciorului la utilizarea camerei TrueDepth a telefonului. Camera TrueDepth care utilizează lumina structurată și aplicația personalizată pentru măsurarea piciorului au caracteristici rapide, precise și ieftine și reprezintă o metodă convenabilă și economică de a obține modelul 3D al piciorului. Se poate aplica pe scară largă în scopuri medicale și de personalizare.

CUVINTE CHEIE: măsurarea piciorului, modelul 3D al piciorului, lumină structurată, cameră TrueDepth

LA VALIDITÉ ET LA FIABILITÉ DE LA CAMÉRA TRUEDEPTH INTÉGRÉE AU TÉLÉPHONE POUR LA MESURE DU PIED

RÉSUMÉ. Il existe plusieurs scanners laser ou à lumière structurée disponibles sur le marché, qui peuvent être utilisés pour obtenir des modèles de pieds 3D précis. Par rapport à ces appareils de numérisation 3D, les caméras TrueDepth sont portables, peu coûteuses et faciles à utiliser. Cependant, la précision et la fiabilité de leur scan 3D du pied restent à confirmer. Cette étude a le but à vérifier la validité et la fiabilité de la caméra TrueDepth à lumière structurée intégrée au téléphone mobile lorsqu'elle est utilisée pour la mesure du pied. Treize étudiants sans aucune sorte d'anomalie ou de maladie du pied ont été recrutés et leurs pieds ont été mesurés à la fois par un scanner de pied 3D et par un téléphone portable avec une caméra TrueDepth. Trois paramètres ont été mesurés, notamment la longueur du pied, la largeur du pied et le tour de pied. Par la suite, la fiabilité et la validité des deux méthodes ont été évaluées par des analyses de régression linéaire, par le coefficient de corrélation intraclasse et par l'analyse de Bland-Altman. Les mesures de la largeur du pied et de la circonférence ont montré des coefficients de détermination élevés (R^2 > 0,8) entre les deux méthodes et trois mesures ont indiqué des accords bons à excellents (ICC > 0,9), bien que la mesure de la longueur ait été rapportée sans coefficients de détermination significatifs. De plus, les résultats de l'analyse de Bland-Altman ont démontré que les mesures de la caméra TrueDepth avaient de bons accords avec celles du scanner Infoot et qu'elles pouvaient être utilisées de manière interchangeable. Cependant, avec la mise à jour de l'algorithme de reconstruction dans un proche avenir, nous pourrions prévoir le progrès de la mesure de la longueur du pied lors de l'utilisation de la caméra TrueDepth intégrée au téléphone. La caméra TrueDepth utilisant la lumière structurée et l'application personnalisée pour la mesure du pied ont des caractéristiques rapides, précises et peu coûteuses et représentent une méthode pratique et économique pour obtenir le modèle 3D du pied. On peut l'appliquer largement à des fins médicales et de personnalisation.

MOTS-CLÉS : mesure du pied, modèle 3D du pied, lumière structurée, caméra TrueDepth

INTRODUCTION

Foot measurements play an important role in the design of footwear, foot orthotics and insoles, which are related directly to fitting, comfort and health [1, 2]. Wearing poorly fitting shoes may increase the risk of lower extremity musculoskeletal problems such as foot pain or deformity [3]. Especially with the advent of mass customization in the area industry 4.0, accurate foot measurement and feasible foot model reconstructions are important considerations when choosing footwear for consumers [4].

There are several methods for measuring foot: manual measure, radiography scanning, laser scanning and optical scanning. Manual measurement is easy-to-use and pervasive, however, lacks repeatability and reliability. Other methods such as laser and magnetic resonance are precise but remain expensive, complex in structure and lack convenience [5], and they were mainly applied to industrial, clinical and research areas [6].

Researchers have compared the strengths and weaknesses of various foot measurements methods. In terms of optical scanning, radiographic such as X-rays allowed exact measurements of the bony structures, however, the radiation was harmful to health [7]. Laser scan such as Infoot 3D foot scanner exhibited good validity and reliability compared with X-rays and clinical measurements [8]. Mall [7] indicated that photographic and caliper measurements had good reliability and acceptable validity to radiographic measurements. Further, Niu [4] first collected 84 foot images with the mobile phone camera and used a magazine as the calibration; and then they constructed the model with Structure-from-Motion algorithm and Patch-based Multi-View System; finally they applied Meshlab to process and measure the foot model. The error of result was around 1mm compared to digital caliper and foot scanner; on the other hand, the operation was inconvenient.

With the advance in optoelectronic technology and mathematical modelling technology, optical scanning became more and more prevalent in the domain of measurement [9]. Both the detailed information on the contours, volume and cross-sectional of the object, and even the dynamic changes in anthropometric measurements [10, 11] could be assessed by optical scanning. With the birth of TrueDepth camera, it was enhanced by the computer vision technology and the advent of depth sensors and then breaks the limits of conventional optical scanning. Weiss *et al*. indicated that a single Microsoft Kinect sensor was capable to create 3D body models with the similar accuracy of expensive and a complex commercial laser scanner [12]. Meanwhile, Rogati *et al*. [13] assessed the accuracy of a Microsoft Kinect sensor by comparing it with a high-resolution laser scanner when scanning the foot plantar model. Ge Wu [14] first designed a system with six depth cameras PrimeSense scanning simultaneously, and then calibrated the system based on T-shaped checkerboards and iterative closest point algorithm, finally validated the accuracy of the scanner compared to manual measurement. Furthermore, Vogt *et al*. [15] evaluated the scanning precision of LiDAR and TrueDepth camera of iPad Pro by scanning Lego bricks compared with an industrial 3D scanner Artec Space Spider.

Since more and more mobile phones have integrated the TrueDepth camera, scanning with the phone would become a potential protocol in foot measurement owing to its convenient operation, low hardware price and mature software application. However, there was no literature reporting their accuracy and reliability. Therefore, this study aimed to verify the validity and reliability of the structured-light TrueDepth camera from the mobile phone. Based on the current cognition of TrueDepth camera scanning, we assumed that the scanning from the phone would generate good results both in the validity and the reliability in contrast with the professional scanner.

EXPERIMENTAL

Materials and Methods

Participants

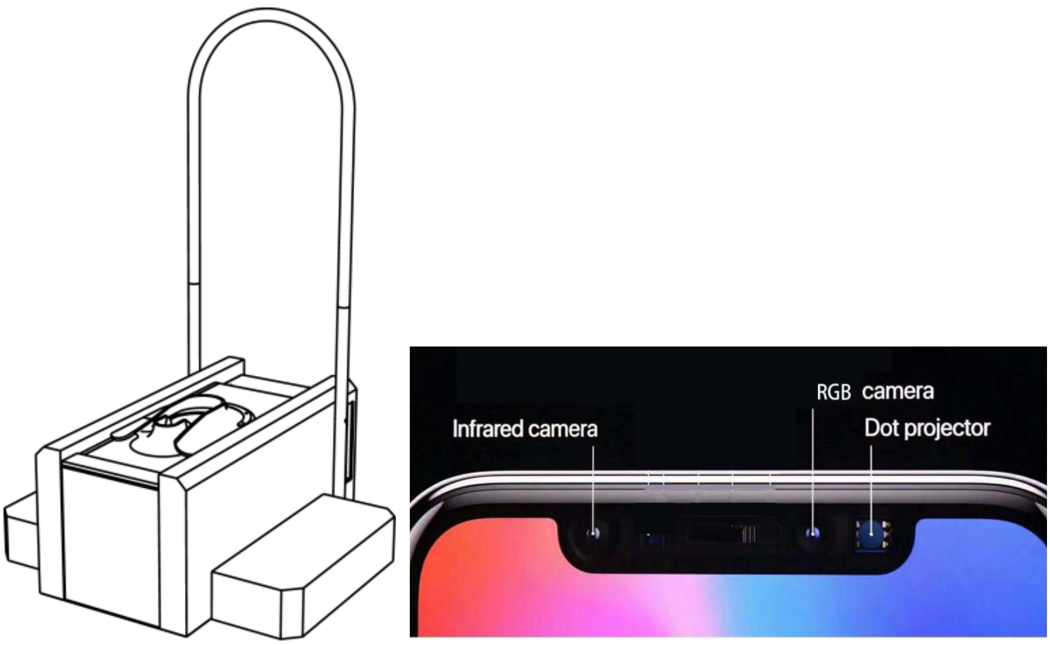
Thirteen students (1 male and 12 females; mean age: 22.7±1.1 years; mean height: 163.3±6.1cm; mean weight: 54.2±8.7 kg; BMI: 20.3±2.64) from Sichuan University were recruited for the experiment. None of them had any kinds of foot abnormalities or foot diseases.

Volunteers gave written informed consent before participation in this study. Due to the variation in the size of the left and right feet and the different size in standing and sitting posture, the two sides of the feet of subjects were measured in both standing and sitting conditions. The experiment was conducted based on principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Sichuan University.

Two Measurement Methods

The feet shapes of the subject were captured using an traditional qualified laser scanner (Figure 1) (INFOOT USB:IFU-S-01, I-Ware Laboratory Co., Ltd., Japan), which is composed of 4 laser projectors and 8 charged-coupled devices (CCD) cameras capturing the lasers. It has shown high repeatability and could be applied directly to the static foot test. The equipment is designed with a multi-view laser path, which scanned a foot shape in less than 10 seconds and obtain high precision point cloud data. The procedure can refer to the operation in this article [16].

Another method was to scan the foot via an iPhone (iPhone XR, Apple inc. USA) with the application of LuxScan. LuxScan is an application based on TrueDepth camera of the phone and it is easy to scan foot models. The structured light-based depth camera (Figure 1) consists of a dot projector, infrared camera and an RGB camera. During the scanning process, the dot projector projects specially structured pattern called laser speckles onto the surface of objects; neural network algorithm in mobile phone bionic chips calculates the 3D shape and depth information of the object based on the distortion of the structured light observed by the infrared camera on the 3D physical surface [17]. The application can quickly generate .stl, .obj and .usdz files within approximately 10 seconds and files can be quickly transferred via sharing.



a b

Figure 1. Two foot-measurement methods. a: INFOOT USB:IFU-S-01; b: The structured light-based depth camera from iPhone

The scanning process of LuxScan is shown below in Figure 2. With the screen side facing downwards, the starting position of the scan was located on outside of the heel diagonally behind the foot within 15-20 cm away from the foot; then the foot was scanned following a circle of 360 degrees within 10 seconds, ensuring that the foot was as still as possible.

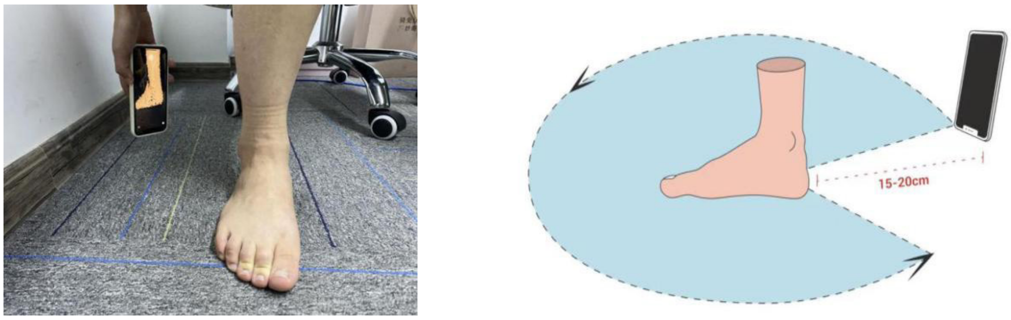


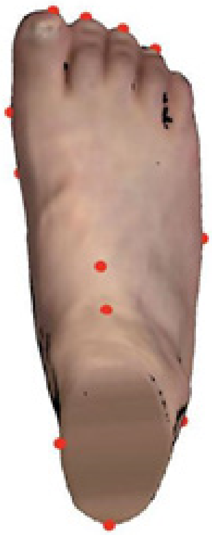
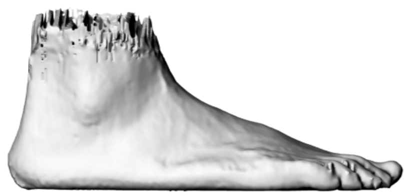
Figure 2. The scanning process of the LuxScan App

After the acquisition by structured light scanning, data were converted to the 3D floating point cloud and a surface reconstruction was conducted to obtain a triangular mesh model. Then, operations such as smoothing, denoising, point cloud alignment and hole repair were performed to obtain a better surface construction. Finally, curved surface reconstruction was carried out and the foot reconstruction data were exported from the scanner in the .obj file format.

Data Procedure and Analysis

In order to contrast the results between the two methods, we exported the STL file of the model and imported them into the Rhinoceros (Version 7.0, Robert McNeel, USA) to measure. An experienced researcher marked and measured the model (Table 1); furthermore, the model obtained from the LuxScan was measured three times for reliability assessment. The following parameters were considered: foot length is the distance from the prominent point of heel end to the tip of the longest toe; foot breadth is the maximum width from oblique length from the first metatarsophalangeal joint to the fifth metatarsophalangeal joint; ball girth circumference is the maximum distance around the circumference at the level of the first and the fifth metatarsophalangeal joint protrusion. These three parameters are most frequently used in the fitting and comfort assessment.

Table 1: An overview of foot 3D reconstruction with two methods

Angle of view	3D model by the structured light camera	3D model by Infoot
Top		
Lateral		
Medial		

With regard to the validity, the correlation between the results of LuxScan and Infoot was explored. Linear Regression Analyses was applied in the research, where results of the app were as independent variables, those from Infoot were as dependent variables. The coefficient of determination (R^2)<0.09 showed a small correlation; 0.09<R^2<0.25 represented a medium correlation; R^2>0.25 indicated a large correlation [18]. In addition, Bland-Altman analysis was used to compare the consistency of two measurements by quantifying their agreement accurately [19].

When considering the reliability, Intra-class correlation coefficients (ICCs (2,1)) were used to indicate the relative reliability of the measure [20]. The ICC<0.5 showed a poor agreement; 0.5<ICC<0.75 showed a moderate agreement; 0.75<ICC<0.9 represented a good agreement; ICC>0.9 showed an excellent agreement. Values of the 95% confidence interval of the ICC less than 0.5 indicate poor reliability. Values ranging from 0.5 to 0.75,0.75 to 0.90, above 0.90 indicated moderate reliability, good reliability and excellent reliability, respectively [21].

All statistical analyses were calculated using software SPSS (23, IBM, USA) with a significant level of 0.05 and a confidence interval of 95%.

RESULTS AND DISCUSSIONS

Results

The coefficients of determination (Table 2) of foot breadth and ball girth circumference were represented with large correlations (R^2=0.85, p=0.007<0.05; R^2=0.90, p=0.001<0.05). However, in terms of foot length, the coefficient of determination was nonsignificant (R^2=0.94, p=0.06).

The ICCs of foot length and foot breadth reached good to excellent agreements, ICC=0.94, p=0.00, 95% confidence interval =0.757 to 0.978 for foot length, ICC=0.92, p=0.00, 95% confidence interval =0.863 to 0.953 for foot breadth. It witnessed an excellent reliability for ball girth circumference (ICC=0.95, p=0.00 and 95% confidence interval =0.910 to 0.969).

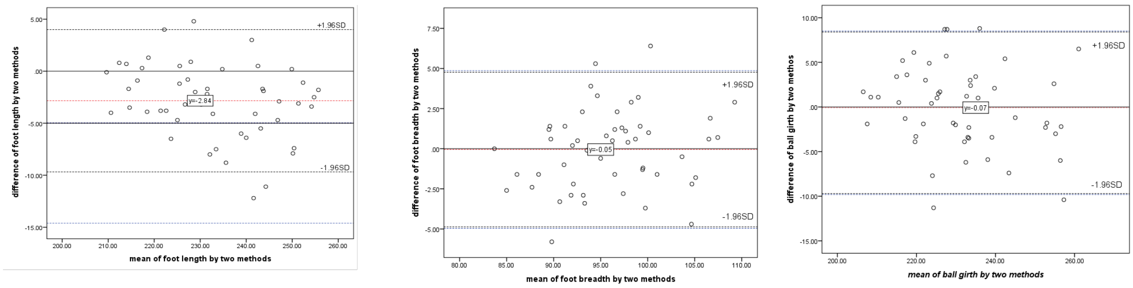
The Bland-Altman analysis was shown in Table 3. The mean bias between two measurements in foot breadth (-0.05±2.46, p=0.89>0.05, 95%LoA=-4.87 to 4.77) and ball girth circumference (-0.07±4.62, p=0.92>0.05, 95% LoA=-9.70 to 8.40) were low, but those in foot length became high (-2.84±3.49, p=0.00). It can be seen from Figure 3 that 6% (3/52) and 10% (5/52) plots were out of the 95% LoA and the discrepancies were accepted in the foot measurements of foot breadth and ball girth respectively. Those findings indicated that the new method can take place the traditional one in terms of the measurements for foot breadth and ball girth circumference, with p=0.919>0.05 and p=0.884>0.05 respectively and no statistically significant differences were found in measurement values. As regards length measurement, the difference of measurement methods was -2.84±3.49, 95% LoA = -9.68 to 4.0 and p=0.00, which indicated that the two methods showed a significant difference in foot length measurement.

Table 2: The regression models and the intraclass correlation coefficients [ICC (2, 1)] for three measured using Infoot and LuxScan

Parameters	Infoot	TrueDepth camera	R^2	ICC (2, 1)	95% CI for ICC (2, 1)
Foot length	231.4±12.53	234.0±13.55	0.936 (p=0.06)	0.943 (p=0.00)	0.757 to 0.978
foot breadth	96.0±6.28	96.0±5.84	0.846 (p=0.007<0.05)	0.919 (p=0.00)	0.863 to 0.953
Ball girth circumference	231.3±13.59	231.4±14.51	0.899 (p=0.001<0.05)	0.947 (p=0.00)	0.910 to 0.969

Table 3: Fixed biases by Bland-Altman analysis of foot measurements using Infoot and LuxScan

Parameters	mean difference ± SD	95% CI for bias (p value)	95% LoA	95% CI for lower LoA	95% CI for upper LoA
Foot length	-2.84±3.49	-3.81 to -1.87 (p=0.000)	-9.68 to 4.0	-14.61 to -4.75	-0.93 to 8.93
foot breadth	-0.05±2.46	-0.73 to 0.64(p=0.919>0.05)	-4.87 to 4.77	-4.96 to-4.78	4.68 to 4.86
Ball girth circumference	-0.07±4.62	-1.35 to 1.22 (p=0.884>0.05)	-9.70 to 8.40	-9.81 to -9.5	8.29 to 8.51



a b c

Figure 3. The plot of foot measurements difference against the mean of the two methods. a. foot length, b. foot breadth, c. ball girth

Discussion

A cognition for TrueDepth camera were established in the literature currently. Deng *et al*. [22] contrasted the consistency of the PrimeSense 3D sensor with conventional CT scan by scanning body surface, and ICC=0.56 for external Haller, 0.80 for depth ratios indices, r=0.63 for external Haller and r=0.84 for depth ratios. Vogt [15] evaluated the accuracy of iPad Pro (2020) TrueDepth camera using Heges app to scan simple Lego bricks and tolerance were 1 mm deviation in average on position, 1.03 mm deviation on profile of a surface, 4.92 mm on Profile of a line, 0.44 mm on straightness, 0.41 mm on flatness, 0.82 mm on cylindricity and 1.17 mm on roundness. Those finding above implied that the TrueDepth camera would be a qualified protocol in object dimension measurement. Very few were found in the literature to assess the accuracy of 3D foot model construction obtained by TrueDepth camera of the phone. A similar one was reported in our previous study. We [23] validated the accuracy of Intel RealSense SR300 camera with a traditional manual method which the results demonstrated that mean differences ranged from -1.3 mm to 5.2 mm and eight measurements parameters exhibited no significant differences. Results from this study further confirmed the above findings. At first, foot measurements from two methods were high-correlated, which witnessed its good measurement validity and accuracy. Then the ICCs of all three measurements all showed good to excellent agreements. At last, a discrepancy was found in foot length measurement using two methods, which might be due to the ambient lighting, inappropriate angle and distance of phone during the scanning [24, 25]. In addition, the meshing and surface fitting during processing was likely to lead to poor point cloud alignment and repair. Those defects can be improved by more tries of standard and steady operation posture and modified reconstruction algorithm. Therefore, our hypothesis was approved.

Although positive results were obtained, limitations still existed. On the one hand, the App requires high configuration and robustness of hardware and software, memory and computing power of the phone, and can only be installed on iPhones with TrueDepth camera at present. On the other hand, this new protocol requires users to keep the smartphone steady when they hold and rotate in a circle around the foot during the scanning procedure.

Further research should be undertaken to investigate the precision of other parameters of the foot, such as planter 3D reconstruction and plantar pressure, which can be used medically and commercially to customize insoles for those associated with deformity and rheumatoid arthritis and enables widespread personal customization.

CONCLUSIONS

Overall, the scanning app utilizing structured-light TrueDepth camera has fast, accurate and low-cost features and it is an easy-to-use, convenient and low power consumption method to obtain the 3D foot model. It breaks the limitation of occasion, tedious operation and heavy costs like professional equipment and it can be widely applied for medical purposes such as orthopaedic shoe customization, medical diagnosis and surgical assistance.

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