Dynamic foot scanning. A study on the accuracy and repeatability of capturing the plantar surface of the human foot while walking using fringe projection methodology.

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INTRODUCTION

The optimal fit of shoes and insoles is not only a crucial factor for subjectiv well-being but also for the prevention of pressure marks and foot pain. Even though there are several kinds of foot scanners which provide high accuracy, the analysis of the human foot shape during walking has not yet been realised. Up to now, most investigations have been perfomed in static, semi-weight-bearing conditions. Recent studies show considerable differences in static and dynamic conditions, as well as in loaded and unloaded foot structure [1,2]. Therefore, the aim of this project was to develope a 3D-scanner-system, combining high resoltion with short recording time, to capture the dynamic foot shape during the roll over process (ROP) of walking.

This study examines the accuracy and repeatability of this new measurement approach.

METHODS

The measurement system is based on the structured light method, where a series of fringes is used to provide 3D-shape information. Three synchronized scanner units, each consisting of one CCD-camera with a resolution of 320 x 240 pixels, and one projector, were used to capture the plantare foot shape during the ROP. The measurement devices were placed below a safety glass platform (60 x 40 cm) which was integrated into a walkway of 460 cm length and 80 cm height. With this setup, the foot could be captured at a frame rate of 41 fps under natural walking conditions.

To quantify the quality of this new measurement approach without knowing the exact values of the dynamic foot shape the absolute and relative (in % of the total foot measurement) Root Mean Square Error (RMSE) [4] and the Limits of Agreement (LoA) displayed in the Bland and Altman plot [5] were calculated as a measure of repeatability. Therefore, the subjects (n=30, 39.7 ± 14.4 years, BMI 25.9 ± 4.81) walked barefoot at a predefined speed of 4.5 km/h ± 5%, which was controlled using photo cells. After an adequate adaptation phase they performed three dynamic trials and two static trials. The static measurements were performed in a semi-weight-bearing situation with the bodyweight evenly distributed on both feet.

The data were evaluated manually using intersection planes (Geomagic Qualify 8). Eight measurement values for foot length and width, and the structure of the medial longitudinal arch (Tab.1) were analyzed in different stance phases defined by de Cook et al. [3].

RESULTS AND DISCUSSION

The absolute RMSE of the repeated measurements in dynamic and static conditions differed between 0.43 mm and 4.19 mm, depending on the measurement (Table 1). Whereas the width and length measures showed relatively low variability (RMSE and LoA), the arch height had the largest variability. When looking at the relative RMSE, these differences become even more obvious, with 1% in foot width / length measures and 8% in arch height. The ball angle showed a low absolute RMSE but had a high relative value of 6.8%.

By dividing the ground contact into different stance phases, the RMSE and LoA were significantly lower in loaded foot parts (e.g. heel width in First Metatarsal Contact) than those in unloaded foot areas (e.g. heel width in Heel off). Overall, the measurement error (RMSE and LoA) for the dynamic measurements was lowest in forefoot flat (FFF) with an average value of 1.24 mm for foot width and length measures. Taking into account that the true value of a measurement (α=0.05) is expected to be within 1.96 x RMSE, the results show that the with of the dynamic foot shape can be displayed width an accuracy of 1.6 mm (0.9%) and the length measures with an accuracy of 3.0 mm (0.8%). Comparing the reproducibility of the static and the dynamic measurements, the static situation shows lower RMSE and LoA in all measurement values.

Table 1: Absolute and relative RMSE of repeated measures

	Stance Phase			
measurement values	**FMC**	**FFF**	**HO**	**static**
ball length (mm / *%*)	1.72 / *0.9*	1.53 / *0.8*	1.58 / *0.9*	1.15 / 0.6
ball angle (degree / *%*)	1.47 / *7.8*	1.28 / *6.6*	1.29 / *6.0*	0.92 / *4.7*
heel width (mm / *%*)	0.43 / *0.6*	0.6 / *0.9*	0.74 / *1.3*	0.44 / *0.7*
ball width (mm / *%*)	1.18 / *1.3*	0.84 / *0.9*	0.8 / *0.8*	0.61 / *0.6*
arch height (mm / *%*)	2.95 / *8.1*	2.93 / *8.8*	4.19 / *11.1*	2.64 / *8.3*

FMC: First metatarsal contact; FFF: Forefoot flat; HO: Heel off

CONCLUSION

The fringe projection method is a suitable technology for capturing the human foot shape. The measurement error for most values was within an acceptable range. Nevertheless, automation of the evaluation process, as well as the addition of further scanner units to capture the entire foot should optimize the repeatability and accuracy of measurements.

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