Clinical Research on Foot & Ankle

ISSN: 2329-910X

Short Communication Open Access

Utilizing Multi-View Depth Sensors, A Quick Tool is Available to Assess the Foot-Ankle Complex's 3D Movements

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Abstract

Movement disorders of the human foot-ankle complex are a common occurrence, owing to the altered joint mechanics during foot-ground interactions. Diagnostics of such movement disorders will require quantitative tools to evaluate in-vivo foot motions, in particular to the multi-segment/joint foot kinematics (MSFK), during gait. Unfortunately, current MSFK analysis largely rely on conventional technologies, such as skin-marker based motion capturing, video fluoroscopy and dynamic 3D scanning, being extremely time-consuming and costly. In this work, a novel movement tracking method, named the point-cloud foot analysis (PFA), was implemented with multi-view depth sensors, to allow fast evaluations of 3D motions of the foot-ankle complex during gait. Quantitative analysis obtained by the PFA methods and their accuracy relative to the conventional MSFK analysis methods were evaluated. The 3D surface reconstructions of the foot-ankle complex were achieved with a RMSE less than 2 mm. It was proven to be feasible to track multi-segment foot motions in both healthy and diseased subjects during walking conditions, with the processing time decreased from more than 4–6 h to less than 6 min for the entire flow of the contact phase analysis. The PFA method can be useful for fast evaluations of the movement disorders of the foot-ankle complex in diagnostics and design of therapeutic interventions and rehabilitation programs for clinical applications However, despite previous efforts, measurement accuracies of above methods may not be sufficient for the analysis of multi-segment foot motions, since the mean joint positioning errors of those methods were no less than 20 mm. To date, a feasible approach that allows efficient evaluation of 3D multi-segment/joint motions for the foot-ankle complex have not yet been established.

Keywords: Biomechanics; Foot model; Joint mechanics; Movement disorders; Depth sensor

Introduction

Therefore, the objective of this study was to design a novel point-cloud based method using multi-view depth sensors, and to allow fast evaluation of 3D movements of the foot-ankle complex in gait. To this end, we proposed a coarse-to-fine registration method for physical calibration of the system and an efficient segment-tracking method for the analysis of foot movement patterns. Quantitative analysis obtained by the PFA and their accuracy relative to conventional MSFK methods were evaluated, and a preliminary study was conduct to analyze multi-joint foot motions in people with diabetes as a first clinical application [**1**-**3**].

To capture 3D point clouds of the entire foot-ankle complex during gait, a valid 3D capture zone was defined. Based on the capture zone, five depth sensors were positioned according to its performance index. The sensor chosen was the Structure Core (Occipital Inc., USA), which had a field of view (FoV) of 59° × 46° × 70° and could achieve 3-mm precision in a 1000-mm range at around 30 frame per second (FPS). Specifically, there were 4 depth sensors (DS0 to DS3 in Fig. 1) placed in the horizontal plane attached to sensor holders to capture upper surface of the foot except for the plantar one. To capture the plantar surface during ground contact, a transparent plate was mounted flush into the walking platform shown in Fig. 1. Sensor DS4 was placed beneath the walking plate, and it was tilted up to avoid specular reflection of the transparent plate and meanwhile lower the height of the walking plate. The current setup allows the entire foot-ankle complex, including plantar surface, to be captured during ground contact phase of walking [**4**-**6**].

The global coordinate system had its origin at the geometrical center of upper surface of the transparent plate, and x direction, y direction, z direction were perpendicular to long side, upper surface, short side of the walking plate respectively.A major challenge in 3D surface reconstruction with multi-view depth sensors is the algorithms are prone to errors due to uncertainty in spatial localization of the 3D point clouds for given sensor poses [**7**]. Thus, a coarse-to-fine registration process based on a custom-designed calibrator is used to ensure the accurate spatial localization of the depth sensors.

Firstly, a coarse registration was performed by adjusting the physical setup of all sensors (e.g., by moving or rotating sensor holders) to ensure a valid 3D capture zone is formed (Fig. 1). A customized calibrator was fabricated for physical calibration of the system. The calibrator was specifically designed to have at least 3 nonparallel planes (every 2 planes are not parallel) for each sensor view. The calibrator was placed on the geometrical center of the transparent plate. We then transformed, merged and visualized point clouds of the captured calibrator in real-time. The coarse calibration was considered done when visualization of the merged point clouds (i.e., 3D surface geometry) approximated the actual shape of the calibrator [**8**].

Secondly, a fine registration was performed by point-to-plane iterative closest point (pl-ICP) algorithm in order to determine the sensor positions represented by transformation matrices with respect to the global coordinate system. The point clouds of the calibrator were captured from 5 different views simultaneously. A 3D registration was performed between the standard point clouds of the calibrator and

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Received: 01-Feb-2023, Manuscript No: crfa-23-88830, **Editor assigned:** 03-Feb-2023, PreQC No: crfa-23-88830 (PQ), **Reviewed:** 17-Feb-2023, QC No: crfa-23-88830, **Revised:** 21-Feb-2023, Manuscript No: crfa-23-88830 (R), **Published:** 28-Feb-2023, DOI: 10.4172/2329-910X.1000391

Citation: David Z (2023) Utilizing Multi-View Depth Sensors, A Quick Tool is Available to Assess the Foot-Ankle Complex's 3D Movements. Clin Res Foot Ankle, 11: 391.

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merged (i.e., captured) data from each view [**9**]. The standard point cloud was directly converted from 3D mesh of the physical calibrator. With the standard point cloud used as target, each merged data acted as source and each pre-defined setup (i.e., sensor position) as its initial pose, the transformation matrix for each source-to-target was calculated.

Here, it is noted that the coarse registration is necessary to ensure good initial positions of each sensor, avoiding a source being registrated to the incorrect targets (since there are many identical planes for the symmetrical design of the calibrator). In addition, the merged data with at least 3 nonparallel planes could effectively reduce registration misalignmentBefore collecting gait data, the subject was asked to walking barefoot on the gait platform back and forth twice (1 set, equals to 4 trials) to familiarize the walking conditions. For each successful trial, the subject should leave a complete footprint onto the transparent gait plate [**10**]. To meet the least requirement, the subject could walk back and forth freely until he/she feels comfortable for data collection.

Discussion

The system continuously acquired data from all sensors while subject walking. However, due to large file sizes of the 3D point clouds (approximately 2 MB per frame from each sensor view), direct acquisition of 3D point-cloud data from multiple sensors would have synchronization issues, leading to difficulties in 3D surface reconstruction. To solve this issue, the original data was saved as depth maps (i.e., raw data from depth sensors). Meanwhile, the corresponding timestamp of each depth map was recorded into local storage for further processing.

In the off-line mode, the depth maps of each view were first converted back to point-cloud data. Then, we synchronized and merged point clouds of all views according to the saved timestamps to obtain the 3D representations (i.e., point-cloud surface) of the foot-ankle complex. Next, to reduce out-of-view noises, each point cloud set was cropped with a bounding box according to the pre-defined capture zone. After cropping, most of the background point data for the ground or reflections were removed.

To isolate the frames of the stance foot (i.e., removing the contralateral swing foot), the bounds to distinguish the stance foot from the swing one in the medial-lateral direction were detected in each frame via programming, and the point clouds were cropped with a bounding box containing only the contacting footFollowing successful tracking, segment transformations corresponding to individual foot frames were obtained. The calculation method for joint kinematics from segment transformations was as follow, since each joint was defined by the relative movements between two segments, the joint transformation can be found by calculating the relative transformation from pose of the distal segment to that of the proximal one.Secondly, joint transformations of each trial were resampled to the same frame length (i.e., corresponding to the same time axis) by spherical linear interpolation.

The resample step ensured each trial performed by the subject would have equal number of frames, such that the algorithms developed in the study could process multiple trials simultaneously. Since spherical linear interpolation is a method for quaternion interpolation only, the transformation matrices were converted to quaternions and converted back to transformation matrices after spherical linear interpolation. Finally, to calculate joint kinematics from the resampled transformations, two sub steps were required, namely the joint kinematics definition and the rotation sequence selection. In sub step 1, joint kinematics were defined as Euler angles of the 3D movements between two segments in three anatomical planes (i.e., sagittal, transverse and frontal). For each segment, the local coordination system was found through principal component analysis. Following the ISB recommendations.

The definitions of foot kinematics were defined as follows: dorsaflexion (positive) and plantar-flexion (negative) as rotation in sagittal plane; adduction (positive) and abduction (negative) as rotation in transverse plane; inversion (positive) and eversion (negative) as rotation in frontal plane.In sub step 2, to calculate Euler angles from joint transformations, an ordered sequence for rotation representation is needed, since different rotation sequence about the axes may reach a same pose. According to the study of Sinclair, we adopted the sagittal-frontal-transverse sequence to calculate Euler angles from transformations. Based on definitions of our global coordinate system, the sagittal-frontal-transverse sequence corresponded to the X-Z-Y axes.

Conclusion

To conclude, a depth sensor-based measurement method, named the Point Foot Analysis (PFA), was developed to facilitate fast evaluation of in-vivo foot motions in gait. The study showed that (i) with a coarse-to-fine registration method, 3D surface reconstructions of the foot-ankle complex could be achieved with RMSE values less than 2 mm; (ii) it was feasible to track multi-segment foot motions in both healthy and diseased subjects during walking conditions; (iii) the efficiency of the PFA system significantly outperformed those of the existing methods. Future efforts should be made to improve the tracking stability of the system when dealing with specific moments with high instantaneous velocity. The characteristics of high efficiency ensured its potential as a valuable tool in the area of foot and ankle research, such as diagnostics for movement disorders and biomechanical intervention applications for the human foot-ankle complex in clinical scenarios.

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