Research Article

KineFeet: A Novel Depth Camera-Based Web Application for Diagnosing Foot Kinematics Alterations

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Running Title: KineFeet for Foot Kinematics Assessment

Abstract

Background: Altered foot kinematics during walking, including reduced tibial inclination (the angle between the tibia and a vertical line during gait), as well as medial longitudinal arch (MLA) flattening and first metatarsophalangeal (MTP1) extension angle have been linked to various musculoskeletal disorders. Such abnormalities can have considerable clinical ramifications; hence, it is essential to identify them accurately.

Aim: We aimed to assess the diagnostic accuracy of KineFeet, a web-based application that employs a depth camera technique to detect foot kinematic changes for human gait analysis.

Methods: KineFeet and Kinovea® gait analysis software were used to diagnose altered foot kinematics in 89 healthy participants in this cross-sectional study. The main kinematic parameters investigated were Ankle Inclination angle at Terminal Stance (AI_TSt), Medial Longitudinal Arch angle at Terminal Stance (MLA_TSt), and Metatarsophalangeal angle 1 at maximal hallux extension (MTP_HE). Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and the receiver-operating characteristic area under the curve (AUC) were computed.

Results: KineFeet showed excellent diagnostic performance. AI_TSt had a sensitivity of 88.23% and a specificity of 95.83%, with PPV and NPV values of 83.33% and 97.18%, respectively (AUC = 0.97). MLA_TSt and MTP_HE also had high discriminative abilities, with sensitivities of 79.54% and 79.00%, specificities of 95.55% and 91.30%, and attributed AUCs of 0.94 and 0.91, respectively.

Conclusion: KineFeet was able to accurately detect foot kinematics deformity during human gait. Its high diagnostic accuracy makes it a promising screening and evaluation tool. Further studies on human gait pathologies are warranted.

Keywords: Gait analysis; Foot; Computer-assisted diagnosis; Kinematics

Introduction

Foot problems are among the key factors that significantly impact gait function. Disorders such as muscle weakness, joint stiffness, or anatomical deformities can alter foot kinematics, subsequently affecting walking efficiency, stability, and smoothness [1,2–5]. Kinematic abnormalities during gait are typically assessed using motion analysis systems. However, these systems require expensive equipment, complex procedures, substantial processing time, and highly trained operators [6,7]. These limitations pose significant challenges, particularly in primary healthcare facilities or resource-limited settings.

Depth camera–based systems designed for clinical use have emerged as a potential solution [8]. To address this issue, we developed Kinefeet, a web-based prototype application utilising depth camera technology to assess foot kinematics in a non-invasive and real-time manner. It is designed as a cost-effective and practical alternative to evaluate joint dynamics during the stance phase of gait. Designed for use with the Microsoft Azure Kinect depth camera, KineFeet enables automatic measurement of ankle angle, subtalar angle, medial longitudinal arch (MLA), ankle inclination (AI), and first metatarsophalangeal (MTP1) angles in both sagittal and frontal planes. The application was developed through an iterative design process involving clinician input, allowing real-time kinematic analysis, cloud-based data storage, and convenient access via standard computers, particularly in clinical or research environments where high-end motion analysis tools are unavailable.

Our previous study demonstrated that KineFeet achieved moderate to excellent test–retest reliability, with Intraclass Correlation Coefficient (ICC) values ranging from 0.78 to 0.98 [9]. Validity testing against manual measurements using Kinovea further showed no significant differences in the ankle inclination angle at terminal stance, in the medial longitudinal arch angle from terminal stance through initial swing, and in the metatarsophalangeal angle across all assessed phases. These findings suggest that KineFeet provides good validity particularly during the mid-to-late stance phases of gait, when joint excursions are larger and clinically relevant abnormalities are most likely to appear [9].

In this study, we aimed to assess how KineFeet can detect kinematic changes in the foot during walking. Diagnostic testing is essential to determine how KineFeet can identify foot kinematic abnormalities that are relevant to function and to evaluate its potential as a clinical screening and diagnostic tool. According to the literature, foot function involves three rockers: the heel (first rocker), the ankle (second rocker), and the forefoot (third rocker). These rockers facilitate forward leg movement over the stable foot [10,11].

During the second rocker, the tibia progresses forward over a stationary foot through active ankle dorsiflexion, primarily controlled by eccentric contractions of the soleus and gastrocnemius muscles. Disruptions in tibial inclination, as quantified by the AI parameter, may impair forward progression and increase the risk of inefficient gait patterns [1]. The third rocker initiates as the heel rises and the toes remain in contact with the ground, with the forefoot acting as a pivot. Effective forward propulsion depends on ankle plantarflexion and the MTP1 joint acting as a fulcrum. Limitations in MTP1 dorsiflexion can impair push-off mechanics, reduce gait efficiency, and alter rollover dynamics [12-14].

However, our previous study also reported that the ankle angle, representing the foot's first rocker, and the subtalar angle, reflecting frontal-plane subtalar joint motion measured using KineFeet, differed significantly from manual measurements, and were therefore considered less suitable for inclusion [9]. Accordingly, in the current diagnostic study, the ankle angle and subtalar angle were excluded from the parameters assessed.

Additionally, the MLA functions as a dynamic shock absorber during midstance to push-off, flattening during foot contact and recoiling during propulsion. The midtarsal joint modulates arch stiffness and flexibility, and pathological alterations such as arch collapse or excessive pronation can lead to chronic gait abnormalities, joint pain, and overuse injuries [15–20]. By focusing on AI, MLA, and MTP1, this study aims to identify core biomechanical indicators associated with dysfunctions in each rocker phase and to provide a comprehensive assessment of foot kinematics not routinely captured by conventional motion analysis systems.

Materials and methods

Study Design

The study was a cross-sectional diagnostic investigation and employed an observational analytic research design. Data were collected at the Department of Physical Medicine and Rehabilitation, Dr. Cipto Mangunkusumo General National Hospital (Central Jakarta, Jakarta, Indonesia) and were approved by the Ethics Committee of Universitas Indonesia (Ethical Approval Number: KET- 1736/UN2. F1/ETIK/PPM.00.02/ 2024).

Participants

This study included 89 healthy participants recruited via consecutive sampling. The inclusion criteria specified that participants should be between the ages of 25 and 59 years old, not using any orthoses or gait support devices, and be able to walk on a treadmill at a minimum speed of 3 km/h. Anamnesis and physical examination were conducted to rule out lower limb deformities. Anamnesis included assessment of participant characteristics and ensuring there were no pain complaints or severe deformities, while the physical examination involved evaluation of ankle and foot joint range of motion, muscle strength, and observation for significant deformities. Additionally, the navicular drop test was performed to assess foot posture and identify the presence of flatfoot or pronation abnormalities. All participants gave written consent. The dropout criteria applied to individuals who could not complete the examination.

Instrumentation

KineFeet gait analysis software was developed through collaboration between the Department of Physical Medicine and Rehabilitation, the Medical Technology Cluster, and a private technology company. The system requires a treadmill, Microsoft Azure Kinect Camera (Microsoft, Redmond, WA, USA), tripods, softbox lighting, and standing backdrops alongside the treadmill for video recording (Fig. 1). The tripods held cameras 40 cm above the floor and 52 cm apart. The camera was connected to a computer via auxiliary cables and USB-C cables for the local KineFeet application and data storage. The Microsoft Azure Kinect is a depth-sensing camera that uses time-of-flight technology to capture precise three-dimensional spatial data alongside high-resolution RGB images. This combination enables accurate tracking of foot and lower limb joint movements in three planes. The kinematic parameters, namely, MLA, ankle, metatarsophalangeal (MTP), and subtalar joints, were measured automatically by the KineFeet web application. Kinovea® (version 2023.1.2) was used to manually measure the same kinematic angles on the same video to compare with KineFeet. Kinovea® has shown high observational reliability for measuring MLA, MTP1, and the AI angles at various speeds.

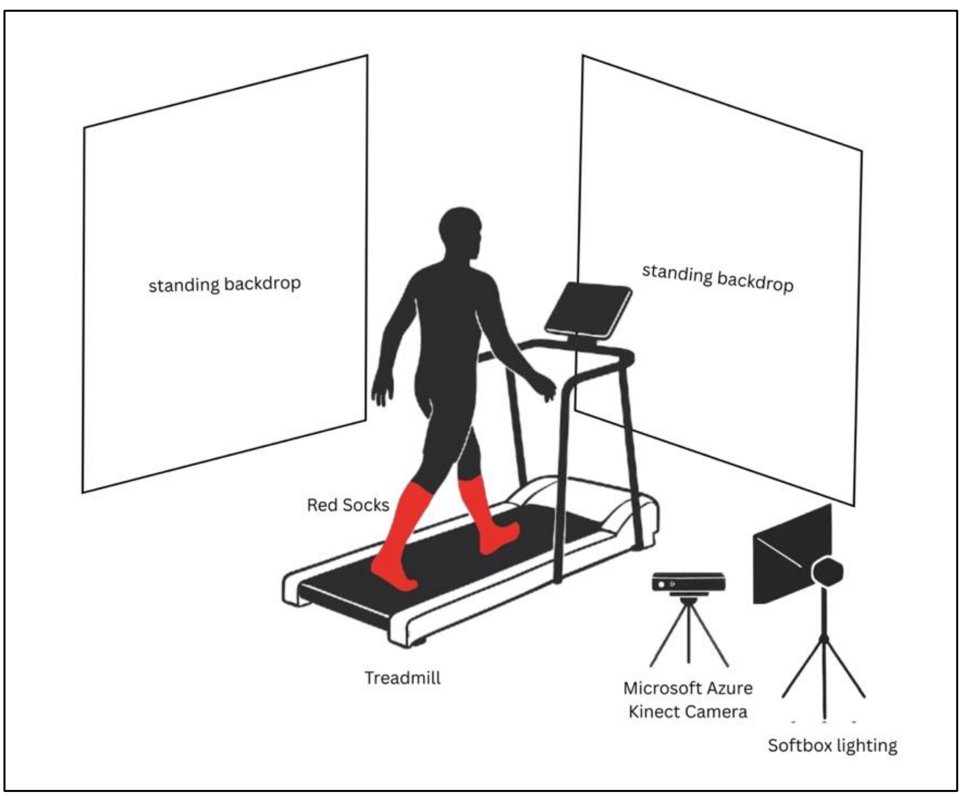

Fig. 1. Overview of the experimental set up including the cameras employed.

Data Collection Procedure

The entire research assessment was done in one session. Each participant received a detailed protocol briefing before the evaluation. This protocol included a KineFeet gait analysis and a physical exam to rule out lower limb deformities. Before the assessment, age, sex, weight, and height were carefully recorded. After it had been established that the participants had no lower limb abnormalities that could affect their gait, foot kinematics measurements were taken.

Participants in the KineFeet gait analysis wore above-knee shorts and knee-length red socks, to which seven white markers were affixed at the bony landmarks of each foot. Marker detection reliability was enhanced through iterative testing and refinement of the KineFeet setup, prioritizing high-contrast visibility by pairing white markers with red socks. The locations for placements for these markers included: 1) the medial aspect of the first distal interphalangeal joint, 2) the head of the first metatarsal, 3) the midpoint between the navicular tuberosity and the head of the first metatarsal on its shaft, 4) the navicular tuberosity, 5) the medial malleolus, 6) the calcaneal tuberosity, and 7) the knee joint line (Fig. 2).

Fig. 2. Photograph showing the placement of markers on the left foot

The study participants were instructed to walk barefoot at a speed of 3 km/h on a treadmill with their arms relaxed and their eyes fixed ahead. To acclimate to the treadmill, its speed was gradually increased from 1 to 3 km/h until consistent performance was achieved. After participants felt comfortable walking on the treadmill, two Azure Kinect devices recorded movements in the sagittal plane for 5 seconds. The KineFeet web application calculated MLA, ankle, AI, and MTP1 joint angles automatically. Validity was assessed by comparing KineFeet results with manual measurements obtained using Kinovea®.

Outcome parameters

The depth camera recorded foot movements during walking in sagittal plane, and measured the range of motion of the talocrural, midtarsal, and MTP joints. The kinematics angles were measured at the end of the sub-phase when the motion reaches the end of its motion range, as per the operational definition presented in Table 1.

Table 1. Operational definitions

Range of Motions	Angle	Operational Definition
Talocruralis	Ankle Inclination angle at the end of terminal stance (AI_TSt)	The angle formed by two lines: a vertical line that passes through the medial malleolus and a line between the medial knee joint line and the medial malleolus, measured when the opposite leg passes the supporting leg, marked when the tibia is on vertical position
Midtarsal	Medial Longitudinal Arch angle at the end of terminal stance (MLA_TSt)	The angle formed by the line between the head of metatarsal 1 and the tuberosity of the navicular and the line between the tuberosity of the navicular and the posteromedial calcaneus, measured when the opposite leg passes the supporting leg, marked when the tibia is on vertical position
Metatarsophalangeal 1	Metatarsophalangeal angle 1 at maximal hallux extension (MTP_HE)	The angle formed by two lines: the line between the midpoint of metatarsal 1 and the head of metatarsal 1, and the line between the head of metatarsal 1 and the medial head of proximal phalange, measured during pre-swing, when the big toes reach maximum extension, just before the metatarsal head lifts off the ground

Statistical Analyses

Statistical analysis was performed using IBM SPSS Statistics software version 29.0 with descriptive statistics. The capacity of KineFeet to detect foot kinematics irregularities during walking was assessed by comparing its results with those obtained via Kinovea® as the reference method. The diagnostic assessment focused on three variables: the AI angle at Terminal Stance (AI_TSt), the MLA angle at Terminal Stance (MLA_TSt), and the joint angle at the Metatarsophalangeal maximum Hallux Extension (MTP_HE). Foot kinematics abnormalities were identified by an AI_TSt value <10°, a first metatarsal dorsiflexion at pre-swing when the hallux extension is maximal value <55°, and an MLA angle >163°.
Standard diagnostic performance formulas based on optimal cut-off thresholds identified through receiver-operating characteristic (ROC) curve analysis were used to calculate

diagnostic accuracy, sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV). The level of statistical significance was set at p <0.05.

Results

The reliability and validity tests were conducted on 89 healthy participants, with the majority of the participants being women (Table 2). The diagnostic analysis revealed that the AI_TSt gait parameter performed the best, with a sensitivity of 88.23%, specificity of 95.83%, PPV of 83.33%, and NPV of 97.18%. Notably, the MLA_TSt and MTP_HE gait parameters also exhibited a robust ability to detect various gait pathologies, with sensitivities of 79.54% and 79%, and specificities of 95.55% and 91.3%, respectively (Table 3).

Table 2. Characteristics of study participants

Characteristics	**Total (n=89)**
Age (mean (SD) y.o)	30.91 (2.55)
Sex	
Women (n (%))	66 (74.2)
Men (n (%))	23 (25.8)
KineFeet measurements	
AI_TST (mean (SD) degree)	12.01 (3.02)
Normal (n (%))	71 (79.7)
Abnormal (n (%)	18 (20.3)
MLA_TSt (mean (SD) degree)	159.5 (7.4)
Normal (n (%))	52 (58.4)
Abnormal (n (%)	37 (41.6)
MTP_HE (mean (SD) degree)	55.6 (10.7)
Normal (n (%))	49 (55.1)
Abnormal (n (%)	40 (44.9)
Kinovea measurements	
AI_TST (mean (SD) degree)	11.9 (3.04)
Normal (n (%))	72 (80.9)
Abnormal (n (%)	17 (19.1)
MLA_TSt (mean (SD) degree)	161.4 (7.92)
Normal (n (%))	45 (50.6)
Abnormal (n (%)	44 (49.4)
MTP_HE (mean (SD) degree)	54.6 (11.02)
Normal (n (%))	46 (51.7)
Abnormal (n (%)	43 (48.3)

An ROC curve analysis demonstrated excellent diagnostic performance for all three gait parameters that were evaluated. The AI_TSt parameter achieved the highest value for area under the curve (AUC = 0.97), indicating an outstanding discriminative capacity. The MLA_TSt and MTP_HE gait attributes also performed well, with AUC values of 0.94 and 0.91, respectively (Fig. 3).

Table 3. Sensitivity and specificity of KineFeet

Variable	Sensitivity (%)	Specificity (%)	PPV	NPV
AI_TSt	88,23	95,83	83,33	97,18
MLA_Tst	79,54	95,55	94,59	82,69
MTP_HE	79	91,3	90	85,71

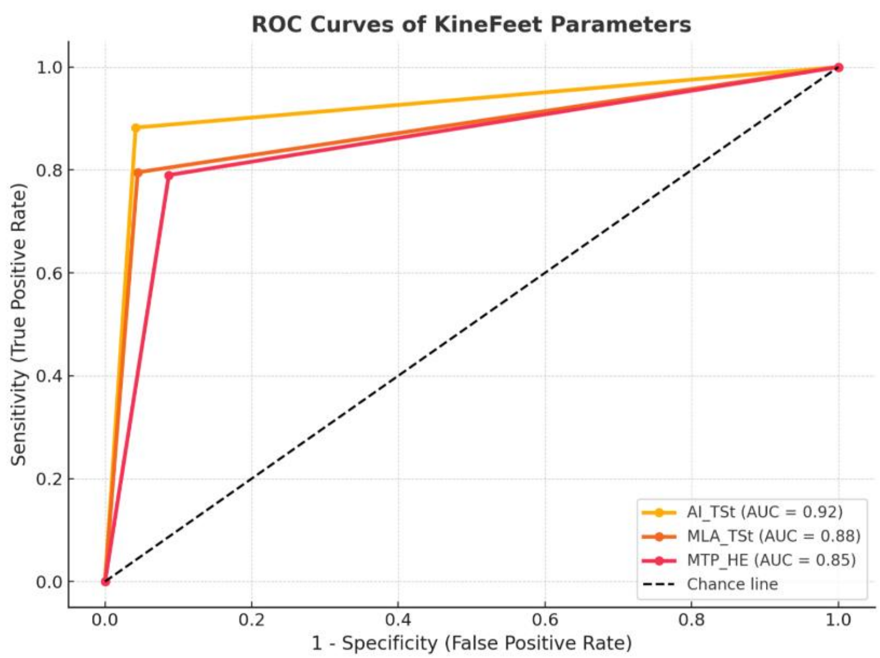

Fig. 3. ROC curves of KineFeet parameters.

Discussion

This study shows that KineFeet provides excellent diagnostic accuracy in detecting abnormal foot kinematics compared to Kinovea. Among the evaluated parameters, AI_TSt exhibited the best performance (AUC = 0.97), with high sensitivity (88.23%) and specificity (95.83%), supporting its clinical relevance as a sensitive indicator of sagittal ankle motion changes during gait. MLA_TSt and MTP_HE also achieved excellent diagnostic values (AUCs > 0.90), indicating their potential usefulness in identifying medial arch collapse and restricted hallux motion, respectively. The consistently high specificity across parameters indicates that KineFeet effectively reduces false-positive results, which is crucial for clinical screening. Its positive and negative predictive values demonstrate that it can accurately detect and rule out gait pathologies, especially those related to the midtarsal region, tibial inclination, and MTP1 joint. The minor differences in average values between KineFeet and Kinovea further support the validity of the depth camera system. These findings align with previous studies emphasizing the importance of ankle and foot segment kinematics, particularly during terminal stance, in identifying gait pathologies [19].

These findings also match other research that has studied depth cameras as motion capture tools. For example, the Kinect v2 has been shown to deliver more consistent spatiotemporal and lower-limb kinematic data than optoelectronic systems, even in clinical populations such as those with cerebral palsy [21]. Likewise, a single RGB-D camera system has been reported to offer acceptable accuracy for gait analysis in healthy individuals and those with polyneuropathy. Follow-up evaluations of the Azure Kinect confirm these earlier findings and indicate promising accuracy for dynamic and kinematic measurements. However, accuracy may be influenced by camera angle and the specific task performed [22, 23]. Direct comparisons between the Azure Kinect and a Vicon system during sit-to-stand tasks showed strong agreement across multiple degrees of freedom [24]. Additionally, a recent systematic review revealed that markerless depth camera systems can provide acceptable reliability and validity for many clinical uses, including gait analysis [21]. Furthermore, research focusing specifically on foot kinematics supports the current study's results. Paterson et al. found that depth cameras can estimate dynamic foot function from static posture, including medial longitudinal arch collapse and rearfoot kinematics [7]. Previous studies have validated RGB-D systems for measuring static arch parameters, such as arch angle and height [25]. Moreover, research has shown that Kinect-based 3D scanners provide accurate and consistent foot morphometric measurements [26].

Taken together, these results position KineFeet among depth camera–based systems with reliable diagnostic effectiveness, sometimes outperforming previous reports. KineFeet's strength lies in focusing on clinically relevant functional parameters (AI_TSt, MLA_TSt, and MTP_HE) during late stance, the gait phase most affected by kinematic deviations. It is also a web-based platform that is easily accessible in both clinical and field settings with limited resources. While the current sample primarily consisted of healthy young adults, which limits generalizability to clinical populations, the findings suggest that KineFeet could be a quick, non-invasive, and accurate screening tool in both clinical and community settings.

However, in this study, both KineFeet and Kinovea detected kinematic abnormalities, specifically reduced tibial inclination (less than 10° of anterior inclination at the end of terminal stance) and dorsiflexion of MTP1 (less than 55° pre-swing when the hallux is maximally extended), in participants with excellent joint mobility and no foot or ankle complaints. These results may be due to participants taking shorter strides to maintain balance, which led to decreased tibial inclination and MTP dorsiflexion.

To assess the accuracy of KineFeet, this study compared its results with manual measurements performed using Kinovea. Kinovea, a widely used two-dimensional motion analysis software, enables manual angle measurements and has been clinically validated as a reliable reference standard, particularly in settings without access to advanced three-dimensional motion capture systems such as VICON®. Previous studies have reported good to excellent intra- and inter-rater reliability for Kinovea (ICC > 0.85), with excellent reliability for MLA and MTP1 angles and good to excellent reliability for AI across various walking speeds [27,28]. Accordingly, Kinovea served as the manual reference for evaluating the measurement accuracy of KineFeet in the three selected parameters.

Limitations and future directions

Despite its encouraging findings, this study has several limitations. Direct comparison with a three-dimensional motion analysis system—the recognized gold standard—was not conducted, as no standardized device exists for the automatic evaluation of AI, MLA, and MTP1 parameters, despite their recognized importance in foot kinematic assessment, and these parameters are not routinely included in conventional motion analysis systems. In addition, the study cohort consisted of healthy adults, which limits the applicability of the findings to individuals with gait disorders stemming from various factors. Future studies should investigate the potential application of

KineFeet-based kinematics analysis to diverse demographic groups and various categories of foot pathology. Nevertheless, the present findings provide a solid foundation for future clinical applications and further technological refinement of KineFeet.

Conclusion

The diagnostic assessments carried out via KineFeet were able to detect foot kinematics abnormalities with a high sensitivity, specificity, and predictive power.

Ethical considerations

Compliance with ethical guidelines

The study was approved by the Ethics Committee of Universitas Indonesia (Ethical Approval Number: KET-1736/UN2. F1/ETIK/PPM . 00.02/ 2024).

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Author contributions

Fitri Anestherita: Conceptualization, formal analysis, investigation, writing – original draft. **Angela B. M. Tulaar:** Conceptualization. **Maria Regina Rachmawati:** Conceptualization. **Em Yunir:** Conceptualization. **Dante Saksono Harbuwono:** Conceptualization. **Retno Asti Wedhani:** Methodology. **Ahmad Yanuar Safri:** Conceptualization. **Muhammad Febrian Rachmadi:** Conceptualization. **Muhammad Hanif Nadhif:** Conceptualization**. Azwien Niezam Hawalie M:** Project administration, Writing – review and editing. **Luh Karunia Wahyuni:** Conceptualization**. Nelfidayani:** Conceptualization. **Boya Nugraha:** Conceptualization.

Conflicts of interest

The authors state that there are no conflicts of interest to declare.

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