Radar Technology as a Mechanism for Clinical Gait Analysis: A Review

Abstract

Walking gait, coordinated by the brain, nerves and musculoskeletal system, is the most common mode of human locomotion and is something that healthy individuals typically carry out every day. Illness or disease affecting these regions may alter gait, leading to declines in an individual’s capacity to function. Consequently, more accessible clinical gait analysis has become important for those affected. The purpose of this review is to gather the most current literature regarding the use of radar, a novel method, for clinical gait analysis. Researchers have found that using radar for clinical gait analysis is more mobile and less invasive than current gold standard methods. Literature tells us that moving forward, research on radar must expand from temporal parameter measurement to spatial parameter measurement as well. Advancements in spatial parameter detection are imperative for radar to reach its potential to positively impact clinical populations.

Keywords

Clinical Gait Analysis; Gait Parameters; Gait Recognition; Radar Signal Processing

Introduction

Human locomotion, commonly known as gait, is a complex coordination of the brain, nerves, and musculoskeletal system. Walking is a gait that healthy individuals typically carry out every day and is our most primitive strategy for maneuvering. An altered gait can become very detrimental to our capacity to function; therefore, gait analysis has become an important assessment for quality of life. The study of human gait dates as far back as Aristotle (384-322BCE) and his theory that humans "rise and fall" during walking. It wasn’t until the 1980s that the creation of modern computers and processing strategies that gait analysis was able to extensively develop [1]. Upon establishment of these modern technologies, several different systems have been implemented into modern gait analysis [2,3].

Since Aristotle’s realization that human walking gait is much more complex than it may initially seem, extensive research has been done on the biomechanics of walking. The two limbs complete the same phases of gait; therefore the cycle can be studied as the time interval between the recurrences of any phase on the ipsilateral limb. It is typically broken up into the stance phase, occurring when the limb being looked at is fully or partially contacting the ground, and swing phase, when the limb is being swung through the air. The stance phase begins with heel strike, when the...
foot makes initial contact with the ground, continues through the swing phase, and concludes with toe off, where the foot is making final contact with the ground and preparing to enter the swing phase. The limb then moves through initial, mid, and terminal swing before once again heel striking.

Any stage of the gait cycle when both feet are contacting the ground (ex. Heel strike on one limb during toe off on the other) is known as single support. Similarly, any stage where only one foot is making contact with the ground is known as single support (ex. During swing phase). Analysis of this cycle is important for several reasons including injury prevention, post-treatment confirmation, sport performance, and evaluating the effects of different human conditions or diseases. The latter is referred to as clinical gait analysis and can be a vital tool in treatment decision making. The purpose of this review is to highlight essential research improvements to be made in the developing field of electrical engineering, and to outline potential growth that could be brought to human movement science.

Data Acquisition

An in-depth search was conducted to find the relevant information. Very few articles exist on using radar for clinical gait analysis, however, there are several articles related to clinical gait issues due to their prevalence in society. Articles were found via Institute of Electrical and Electronics Engineers (IEEE) and Ball State University’s Library One Search journal database by searching for “human gait parameters AND radar”, “clinical gait analysis”, “gait analysis (technology OR methods)”, “classification of human movement AND radar”, “gait analysis AND radar”, “radar sensing for healthcare”, “radar AND gait velocity parameters”, “gait measurement AND radar”, and “radar AND gait parameters”. Article acquisition began in May 2020 and searches were limited to at most the last 15 years, but primarily 10, 5 and 3 years. Therefore, articles that were included in the analysis had a published date of approximately 2005 or newer.

Gait Analysis and Clinical Populations

Clinical gait analysis seems to have been set in motion right around the same time as modern technology emerged [4]. Since then, clinical analysis has proven beneficial to a wide range of populations suffering from abnormal gait. As previously mentioned, gait is coordinated by the brain, nerves, and musculoskeletal system. Therefore, it reasons well that issues in gait arise from musculoskeletal, neuromuscular, and central nervous system disorders [5].

Gait disorder due to musculoskeletal abnormality is known as antalgic gait. This type of gait typically develops to avoid pain that comes with the abnormality and presents a limp in walking. Antalgic gait may be due to lower limb osteoarthritis or skeletal deformities such as differences in leg length, which, among several other causes, may lead to full or partial amputation. Antalgic gait defects are typically seen in the elderly population, regardless of other conditions. Abnormalities contribute to increased energy cost; however, closer inspection of gait may assist physical therapists in recognizing and correcting these factors [6]. Another class of irregular gait is ataxic gait. These gait patterns are usually due to a damaged cerebellum, the region of the brain responsible for regulating and coordinating muscular activity, leading to unsteady, staggering gait [3]. Cerebellar damage can be due to inflammation (e.g., Multiple Sclerosis), developmental issues (e.g., Cerebral Palsy), degeneration (e.g., inherited gene mutations), trauma, etc. [5]. On a less permanent scale, ataxic gait is also a result of excessive alcohol consumption due to its toxic effects on the cerebellum. Additionally, apraxic gait is the inability to carry out purposeful movement and is typically seen in Parkinson’s disease [3]. Parkinson’s disease is known for displaying tremors, and over time affecting ambulation to extremes. Gait research has been done to extract several temporal parameters that distinguish characteristics of gait in early Parkinson’s. It was found that unusual tendencies may become present in early Parkinson’s, and detection would allow for medical treatment and rehabilitation early on, perhaps delaying the overall decline [7].

Due to the pathologies of the aforementioned diseases and conditions, changes in gait are commonly noted side effects. It is important to understand that as these conditions progress, so do alterations in gait [8] and that functional gait has a significant correlation with quality of life [9]. Clinical gait analysis has the potential to assess the severity of lost function so that therapeutic interventions can be implemented along the way, in hopes of slowing the decline. This information would also be of value for early diagnosis [10] and identifying patterns or trends in diseased populations [11].

Current Modes of Analysis

On account of the measurements and parameters that gait analysis offers, the demand for use on clinical populations, as well as in clinical settings, has become quite high [12]. Several methods for gait analysis have enveloped and can primarily be divided into categories of subjective and objective analysis. In terms of subjective analysis, observation is an undemanding method of inspecting gait and is performed by a trained professional [10]. In comparison between observed gait by physical therapists and a 3-D camera technique, it was found that the subjective approach has moderate to good validity and reliability [13], but this method is commonly disregarded as
many issues arise in accuracy and repeatability [14]. Subjective observation of gait can be done by plainly observing walking, or by testing the patient on a predetermined course of action. Timed 25-Foot Walk or the Timed Get up and Go are among several predetermined tests, each highlighting specific parameters that are more pertinent to the patient’s condition. Despite the imperfect nature of humans, observational gait analysis could be a constructive complement to objective quantitative analysis [15].

Objective analysis methods can be subdivided into wearable sensors and non-wearable sensors. Wearable sensors include measurement tools such as accelerometers, goniometers, force sensors, and several other inertial measurement instruments. The advantage of these techniques is that analysis can be done outside of a lab during daily activities, but most are highly sensitive to interference [10] and collect an abundance of information, making it difficult to find what is relevant in a trial [16].

Non-wearable sensors involve parameter analysis done by technologies external to the body and are usually seen in controlled research facilities. Image processing systems are non-wearable and best suited for calculation of spatio-temporal and kinematic gait parameters, with the current gold-standard being infrared 3-D camera systems [17]. The data collected via the system can then be used to create rigid body models [Figure 1]. Other methods include 2-D camera analysis, which ultimately lacks in giving full multi-planar feedback [18], infrared thermography, laser scanning, and the up-and-coming radar system. Although several modalities for analysis exist, there is still much research that needs to be done before gait analysis can be implemented into a regular clinical setting [12].

Despite being current gold-standard, 3-D infrared camera analysis (also known as motion capture) has several drawbacks that are preventing it from being used in clinical settings worldwide. Firstly, motion capture camera systems are exceptionally expensive. This causes them to exist mostly as laboratory-grade systems and consequently lack the ability to detect real-world gait [19]. Additionally, they have not proven to be very mobile, making it difficult to transport systems to convenient locations for the populations in need (i.e., hospital, doctor’s office). Furthermore, 3-D motion capture utilizes a marker-based system requiring participants to have several small, retro-reflective markers placed directly onto the skin in specific anatomical locations. This process may add a level of discomfort for some individuals as well as altered movements, where as a marker-less system would eliminate this [3]. Markers also have the potential to be poorly and inconsistently placed, leading to inaccurate measurements and validity issues in research.

Figure 1: A biomechanical model, created from data collected with 3-D motion capture systems, using Visual 3D software. The creation of a virtual rigid body model from a live human model is a typical step in gait analysis using the motion capture method.
Radar

History

Radar is a system able to detect objects based on propagation and return of electromagnetic waves to its receivers. It was first observed by Russian scientist Alexander Popov in 1897 due to interference from a passing ship. The concept was not introduced to the United States until 1914 and was not well understood until 1922. 14 years later, federal funding for research had been granted and a device was built able to detect planes as far as 40 km away. Advancements continued and radar technology became extremely sought-after throughout World War II, during which it was given its name standing for “radio detection and ranging” [20].

Coinciding in the United Kingdom Sir Watson-Watt (commonly known as the Father of Radar) was pioneering radio detection and radar technology. He worked to develop operationally effective systems which valuable contributed to both ground and airborne war. The implementation of these systems into the military undeniably advanced the United Kingdom in WWII as they were utilized at several critical periods. Although Sir Watson-Watt was not the first man to harness radar, he was the first to successfully apply it to an urgent issue at the proper time [21].

Since then, radar technology has remained useful to the military but has also proven useful in several other fields present in daily life including weather, law enforcement, border protection, sports, gait analysis, etc. In this review, we are focusing on the potential that radar has to make advancements in availability of clinical gait analysis.

Why radar? Comparison to other sensors

Compared to previous systems discussed, radar technology is able to offer several advantages that other systems lack. Mobility is advantageous due to allowing analysis to be done in everyday settings with little to no interference from light sources or weather conditions [22], therefore increasing the external validity of results. In addition to mobility, the small sizes of radars draw attraction in clinical settings due to ease of implementation and transfer around an office. Wearable sensors, like markers required for infrared analysis, decrease comfort ability and may alter patient’s natural gait pattern. Inertial sensors are frequently limited by battery size, refusing long term wear on the lower limbs [16]. Radar systems have the ability to penetrate through clothing [22,23], which may eliminate tendencies to alter gait as well as the privacy concerns that come with marker placement, as tight spandex is the required clothing.

Radar explanations

Active radars come in several different forms, but generally fall into two categories: pulsed or continuous transmission, each name describing the way in which waves are transmitted. The return of waves to the receiver is what provides valuable information such as the range, angle, or velocity of the object being detected. This is achieved by measuring the shift in frequency between the propagated and returned wave, a phenomenon known as the Doppler Effect.

In human movement, it becomes slightly more complex as humans are composed of multiple rigid bodies connected by joints. These rigid bodies do not move with uniform or constant radial velocity [24]. A good example is the swinging of the arms during walking. In proper gait, the leg swings forward relative to the torso, accompanied by the contra lateral arm. Meanwhile, the ipsilateral arm is swinging backward while the torso remains relatively stagnant. Mechanical vibrations or rotations occurring around the bulk translation (the torsion our example) undergo micro-motion dynamics, causing frequency modulation of the returning signal. This generates side bands about the Doppler frequency, referred to as the Micro-Doppler (MD) effect [25].

Time-frequency representation is the common method for radar signal processing in movement analysis, depicted by a spectrogram graph [23,26]. The spectrogram successfully delivers a visual of signal frequencies as they vary with time [Figure 2], however, a drawback to this method is that results cannot be visualized as simplistically as they would be from electro-optical sensors or motion capture systems [27]. Occasionally in research, human walking models are used to help visualize results. Human walking models are built from experimental data, one of the more notable being the Thalmann model [28,29]. Although models help to justify further research and contribute to signal processing algorithms, they do not account for environmental issues nor do they provide real data. Estimated features give good animated visuals; however, models cannot replace experimental data.

Despite the multiple types of radars that exist, the three most experimented with for gait analysis are Continuous Wave (CW), Frequency Modulated Continuous Wave (FMCW) and pulse-Doppler radars. The major downfall of CW radars is that they lack the ability to assess range [30]. FMCW and pulse-Doppler radars are able to provide velocity and range data, making them more suitable to provide both temporal and spatial gait parameters.
Application of Radar to Movement Science

A bulk of the research that has come out regarding radar technology and gait analysis has contributed to detection, recognition and classification of gait. There has since been research aiming to extract temporal parameters of gait, commonly including cadence, velocity, phases, and events of gait, etc. [3]. Advancements that have been made are predominantly in the interests of law enforcement, border control, and search & rescue. Research has also been done using radar to detect falls in elderly populations and to analyze the gait of persons with various diseases.

Human target detection & recognition

Detection of gait is the process of realizing movement is occurring. Research in this discipline has been conducted with the intention of detecting falls in the elderly. A study by Su et al. used a range control Doppler radar and a wavelet transform to sense frequency changes associated with falling. The wavelet transform allowed the detector to pre-screen and classify falls vs. non-falls to help eliminate false alarms. This method showed promise and robust performance [31]. More recent research also used a range-Doppler radar paired with a deep learner approach to successfully detect falls, verified by the ability to distinguish between walking, falling, bending/straightening, and sitting [30].

Detection studies have also been done to assess radar’s ability to successfully identify someone in the course of gait. Vandersmissen et al., completed a study using FMCW radar to identify spontaneously walking persons between multiple rooms. They were able to successfully use MD signatures to identify persons exclusively based on gait characteristics in indoor, realistic situations [32]. Additionally, identification of multiple segments (right foot, left foot, and torso) with in a trial of walking gait was able to be distinguished by Ultra-Wide Band (UWB) impulse radar. This research was the first to use the State-Space Method (SSM) to analyze compressed radar echoes and was validated by comparison to a Boulic model with less than 8% discrepancy [33].

Recognition of gait involves identifying movements based on previous encounters. There are several applications for radar recognition including inmate monitoring and suicide attempt detection [34] in addition to gait recognition [35]. Fine-tuning this task has proven difficult on account of overlapping frequency components of MD and Doppler frequencies and has led to a push in signal separation research. A method recently explored adopted a MD separation algorithm in order to separate MD signals deriving from limbs and the Doppler signal deriving from the torso. The intent of this was to be able to recognize different subjects performing the same activity, which was achieved with about 90% accuracy and above for different group sizes [36].

Human movement classification

Gait classification allows categories to be formed according
to shared qualities or characteristics. As of now, it’s height in popularity lies in law enforcement. In one study, the proposed FMCW radar model was able to classify whether a person was carrying an item or walking freehanded, potentially indicating whether or not someone is armed [37]. Further applications include medical diagnosis, rehabilitation and assisted living. An intra-motion study was done with hopes of being the first of its kind to classify gait within different walking categories such as normal, pathological and assisted walks. The researchers used UWB CW radar and a Fourier Transform to identify and classify the different styles. Gait classification was identified with 93.8% accuracy and a classification rate of 98.5% for an individual class. The study concluded that the sub-space methods chosen were superior to physical features in accurately classifying different gait patterns [38].

Basic gait analysis

More recently, in addition to improving detection, recognition and classification, research has been focused on designing radars to perform simple gait assessments. These assessments were focused on extracting temporal parameters of gait. Van Dorp & Groen used feature-based parameter estimation methods to try and speed up the process of estimating Boulic model parameters, specifically from spectrograms, so that real-time applications could be made. They found the feature-based approach to allow for real-time animation, opening up possibilities for using temporal parameters to quickly recognize gait instead of laggard model animation [27]. This finding contributed to the ease of producing results. In 2014, Wang et al., looked at the accuracy of walking speed and step time for continuous gait assessment of older adults. They set up radars at both torso and foot height. Results were compared to data collected by the gold standard motion analysis system, which was simultaneously capturing data. The pulse-Doppler radar placed at torso height underestimated velocity on average of 9% compared to the motion capture system. Additionally, the radar placed at foot height underestimated velocity on average of 13-18%. A stronger relationship was seen in regards to step time, with an impressive interclass correlation coefficient of 0.97 in terms of consistency and absolute agreement [39].

Furthermore, there has been focus on the extraction of temporal parameters with MD signals. A 2009 study focusing on stride rate concluded that, although they were successful in feasibly extracting stride rate, this parameter alone is not enough to quantify gait [40]. The trouble with parameter extraction emerges due to the complexity of MD signatures, therefore, tackling this obstacle is yet another (and perhaps the most significant) focus of radar research. Isolating segment characteristics is crucial in moving forward with radar [41]. A study was done to test methods for identifying motions of different limb joints during gait using CW radar. The findings of this study show that simple motion such as a hand or leg swing independent of gait can be clearly tracked, however the results become less clear when the motions are concurrent with gait [42]. This research brings to light methods that need improvement in MD research in order for extraction of temporal gait parameters to excel. Separation of MD signals can be done by characterizing echo’s from different body parts. This is typically achieved by using either MD or high range resolution [33] or MD information alone [43]. Qiao et al., recently proposed a novel method for separation based on short-time fractional Fourier Transform and morphological component analysis. Although the proposed algorithm efficiently separated torso and limb signals, more research needs to be done before the method can really contribute to temporal parameters [43].

In addition to temporal parameters, spatial parameters even more so lack development due to both MD hindrance and deficiencies in radar detecting range. Detection, recognition, classification, and temporal parameters only scratch the surface of applications gait analysis has to offer clinical populations.

Clinical gait analysis

In the last few decades, research on radar to analyze human gait characteristics and parameters has considerably increased. The investigation peaked largely due to the modern-day applications of gait analysis. Its potential to help clinically has increased attentiveness to radar specifically within the field of human movement science. Right now, radar is able to detect, recognize and classify gait as well as provide basic temporal parameters, however it lacks in successfully quantifying gait parameters necessary to make strides within clinical populations. Temporal parameters have been able to provide valuable information thus far regarding movement, however, in order to make further advances in clinical gait analysis, research must focus on nailing down spatial parameters so that kinematic parameters may follow (i.e., joint/segment angles, angular motion, acceleration, segment trajectory).

Sun et al., completed a study using MD to estimate motion parameters such as bulk velocity, gait cycle, and cycle length as well as physical parameters such as leg length and height of walking humans [44]. They found their elementary computation methods compared to simulation results to have highest estimation accuracy, however, the most valuable advancement from this research is perhaps the easy measurement of physical parameters. Leg length in particular is a value applicable to calculating segment parameters, which can help advance measurement of spatial parameters as well as characterizing joint kinematics.
Saho et al. used radar to evaluate higher-level instrumental activities of daily living. This study specifically applied radar to a common clinical test (sit-to-stand-to-sit), contributing to the growth of health monitoring systems based on gait parameters. In an effort to extract kinematic parameters, a limitation researchers experienced was lower than expected accuracy due to the use of only one radar, but proposed that accuracy will improve using multiple radars in various places [45]. This study is particular to a specific clinical examination and is the type of research that may take radar analysis to the next level. As more routine scenarios for clinical communities are analyzed, more insight will be able to be provided regarding the delay of diminished quality of life.

Summary

In 2001, Dr. DH Sutherland wrote a paper reviewing the evolution of kinematics in clinical gait analysis. In it, he explains the need for these measurements in order to be able to make comparisons between pathological and normal gait [4]. At the time, 3-D motion capture systems were starting to make waves and as we know, they are still the premier approach. Despite all of the technological advancements that have been made since then, the system’s main disadvantages have not been attended to. Radar is a practical method offerings ever al advantages, most notably mobility and noninvasive, comfortable procedures, which greatly boosts its potential in the field of human movement science. Before it can be fully applied, it is imperative that research takes the next steps by continuing to address spatial parameters, working to improve the quality of measurement, as well as methods to implement kinematic parameters into radar.

Let this review serve as a call to action for engineering researchers to further investigate radar, as well as realize the impact it could have for clinical populations. The extraction of relevant parameters, specifically spatial parameters (step length, stride length, etc.), needs vast improvement for radar to provide accurate range-motion characteristics of gait. More accurate procedures for measuring range may also bring about methods for extracting kinematic parameters such as joint angles, angular motion, segment trajectory, etc. These values provide pertinent information to enable clinicians to make progress with patients.

Acknowledgment

This project was supported by a grant from the Indiana Space Grant Consortium (2019 INSGC).

Conflict of Interests

All authors declare no conflicts of interest in this article.

References

1. Baker R (2007) The history of gait analysis before the advent of modern computers. Gait Posture 26: 331-342.
2. Akhtaruzzaman A, Shafie A, Khan R (2016) Gait Analysis: Systems, Technologies, and Importance. J Mech Med Biol 16: 1.
3. Prakash C, Kumar R, Mittal N (2018) Recent developments in human gait research: parameters, approaches, applications, machine learning techniques, datasets and challenges. Artif Intell Rev 49: 1-40.
4. Sutherland DH (2002) The evolution of clinical gait analysis Part II Kinematics. Gait Posture 16: 159-179.
5. Pirker W, Katzenschlager R (2017) Gait disorders in adults and the elderly: A clinical guide. Wien Klin. Wochenschr 129: 3-4.
6. Wert DM, Brach J, Perera S, VanSwearingen JM (2010) Gait biomechanics, spatial and temporal characteristics, and the energy cost of walking in older adults with impaired mobility. Physical Therapy 90: 977-985.
7. Pistacchi M, Gioulis M, Sanson F, De Giovannini E, Filippi G, et al. (2017) Gait analysis and clinical correlations in early Parkinson’s disease. Funct Neurol 32: 28-34.
8. Severini G, Manca M, Ferraresi G, Caniatti LM, Cosma M, et al. (2017) Evaluation of Clinical Gait Analysis Parameters in patients affected by Multiple Sclerosis: Analysis of kinematics. Clin Biomech 45: 1-8.
9. Khanittanuphong P, Tipchatyotin S (2017) Correlation of the gait speed with the quality of life and the quality of life classified according to speed-based community ambulation in Thai stroke survivors. Neuro Rehabilitation 41: 135-141.
10. Muro-de-la-Herran A, Garcia-Zapirain B, Mendez-Zorrilla A (2014) Gait Analysis Methods: An Overview of Wearable and Non-Wearable Systems, Highlighting Clinical Applications. Sensors 14: 3362-3394.
11. Kempen JCE, Doorenbosch CAM, Knol DL, de Groot V, Beckerman H (2016) Newly identified gait patterns in patients with multiple sclerosis may be related to push-off quality. Phys Ther 96: 1744-1753.
12. Marín J, Blanco T, Marín JJ, Moreno A, Martítegui E, et al. (2019) Integrating a gait analysis test in hospital rehabilitation: A service design approach. PLoS ONE 14: e0224409.
13. Tas S, Güneri S, Kaymak B, Erden Z (2015) A comparison of results of 3-dimensional gait analysis and observational gait analysis in patients with knee osteoarthritis. Acta Orthop Traumatol Turc 49: 151-159.
14. Carse B, Meadows R, Bowers R, Rowe P (2013) Affordable clinical gait analysis: an assessment of the marker tracking accuracy of a new low-cost optical 3D motion analysis system. Physiotherapy 99: 347-351.
15. Littrell ME, Chang YH, Selgrade BP (2018) Development and Assessment of a Low-Cost Clinical Gait Analysis System. J Appl Biomech 34: 1-19.
16. Chen S, Lach J, Lo B, Yang GZ (2016) Toward Pervasive Gait Analysis with Wearable Sensors: A Systematic Review. IEEE J Biomed Health Inform 20: 1521-1537.

17. Galna B, Barry G, Jackson D, Mhiripiri D, Olivier P, et al. (2014) Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson’s disease. Gait Posture 39: 1062-1068.

18. Clayton HM, Schamhardt HC Measurement Techniques for Gait Analysis. Meas Tech 22.

19. Ali A, Sundaraj K, Ahmad B, Ahamed N, Islam A (2012) Gait disorder rehabilitation using vision and non-vision based sensors: A systematic review. Bosn J Basic Med Sci 12: 193-202.

20. Guarnieri M (2010) The Early History of Radar [Historical]. IEEE Ind Electron Mag 4: 36-42.

21. Hanbury Brown R (1994) Robert Alexander Watson-Watt, the father of radar. Eng Sci Educ J 3: 31-40.

22. Geisheimer JL, Marshall WS, Greneker E (2001) A Continuous-Wave (CW) radar for gait analysis in Conference Record of Thirty-Fifth Asilomar Conference on Signals, Systems and Computers 1: 834-838.

23. Tivive FHC, Bouzerdoum A, Amin MG (2010) A Human Gait Classification Method Based on Radar Doppler Spectrograms. EURASIP J Adv Signal Process 1: 389716.

24. van Dorp P, Groen FCA (2003) Human walking estimation with radar. Sonar Navig IEE Proc-Radar 150: 356-365.

25. Chen VC, Li F, Ho SS, Wechsler H (2006) Micro-Doppler effect in radar: phenomenon, model, and simulation study. IEEE Trans Aerosp Electron Syst 42: 2-21.

26. Shi X, Zhou F, Tao M, Zhang Z (2016) Human Movements Separation Based on Principle Component Analysis. IEEE Sens J 16: 2017-2027.

27. Dorp PV, Groen FCA (2008) Feature-based human motion parameter estimation with radar. Sonar Navig IET Radar 2: 135-145.

28. Boulic R, Magnenat-thalmann N, Thalmann D (1990) A Global Human Walking Model with Real-Time Kinematic Personification. Vis Comput 6: 344-358.

29. Quaiyum F, Tran N, Phan T, Theilmann P, Fathy AE, et al. (2018) Electromagnetic Modeling of Vital Sign Detection and Human Motion Sensing Validated by Noncontact Radar Measurements. IEEE J Electromagn RF Microw Med Biol 2: 40-47.

30. Jokanović B, Amin M (2018) Fall Detection Using Deep Learning in Range-Doppler Radars. IEEE Trans Aerosp Electron Syst 54: 180-189.

31. Su BY, Ho KC, Rantz MJ, Skubic M (2015) Doppler Radar Fall Activity Detection Using the Wavelet Transform. IEEE Trans Biomed Eng 62: 865-875.

32. Vandersmissen B, Knudde N, Jalalvand A, Couckuyt I, Bourdoux A, et al. (2018) Indoor Person Identification Using a Low-Power FMCW Radar. IEEE Trans Geosci Remote Sens 56: 3941-3952.

33. Tran N, Foroughian F, Naishadham K, Piou JE, Kilic O, et al. (2018) Short-Time State-Space Method for Micro-Doppler Identification of Walking Subject Using UWB Impulse Doppler Radar. IEEE Trans Microw Theory Tech 66: 3521-3534.

34. Forouzanfar M, Mabrouk M, Rajan S, Bolic M, Dajani HR (2017) Event Recognition for Contactless Activity Monitoring Using Phase-Modulated Continuous Wave Radar. IEEE Trans Biomed Eng 64: 479-491.

35. Ricci R, Balleri A (2015) Recognition of humans based on radar micro-Doppler shape spectrum features. IET Radar Sonar Navig 9: 1216-1223.

36. Qiao X, Shan T, Tao R (2020) Human identification based on radar micro-Doppler signatures separation. Electron Lett 56: 195-196.

37. Ritchie M, Ash M, Chen Q, Chetty K (2016) Through Wall Radar Classification of Human Micro-Doppler Using Singular Value Decomposition Analysis. Sensors 16: 1401.

38. Seifert AK, Amin MG, Zoubir AM (2019) Toward Unobtrusive In-Home Gait Analysis Based on Radar Micro-Doppler Signatures. IEEE Trans Biomed Eng 66: 2629-2640.

39. Wang F, Skubic M, Rantz M, Cuddihy PE (2014) Quantitative Gait Measurement with Pulse-Doppler Radar for Passive In-Home Gait Assessment. IEEE Trans Biomed Eng 61: 2434-2443.

40. Tahmoush D, Silvious J (2009) Stride rate in radar micro-doppler images. IEEE International Conference on Systems, Man and Cybernetics 4218-4223.

41. Park J, Johnson JT, Majurec N, Frankford M, Stewart K, et al. (2014) Simulation and analysis of polarimetric radar signatures of human gaits. IEEE Trans Aerosp Electron Syst 50: 2164-2175.

42. Quaiyum F, Tran N, Piou JE, Kilic O, Fathy AE (2019) Noncontact Human Gait Analysis and Limb Joint Tracking Using Doppler Radar. IEEE J Electromagn RF Microw Med Biol 3: 61-70.

43. Qiao X, Shan T, Tao R, Bai X, Zhao J (2019) Separation of Human Micro-Doppler Signals Based on Short-Time Fractional Fourier Transform. IEEE Sens J 19: 12205-12216.

44. Sun Z, Wang J, Sun J, Lei P (2017) Parameter estimation method of walking human based on radar micro-Doppler. IEEE 2017: 0567-0570.

45. Saho K, Uemura K, Fujimoto M, Matsumoto M (2020) Evaluation of Higher-Level Instrumental Activities of Daily Living via Micro-Doppler Radar Sensing of Sit-to-Stand-to-Sit Movement. IEEE J Transl Eng Health Med 8: 1-11.