Transforming Care: AI-Powered 3D Gait Analysis using a Single Consumer-Grade Camera

'Measure what can be measured and make measurable what cannot be measured.' – Galileo Galilei.

1. Introduction

We are at the threshold of a transformative era in healthcare, an era where the power of machines is being harnessed to gain profound insights into the human condition. The study of kinematics is core to our understanding of both normal and abnormal human biomechanics and movement processes. It is beneficial in analyzing healthy bodily motions and assessing and managing abnormal gait, injuries, and numerous pathophysiological conditions. In the realm of healthcare, the application of kinematic evaluation is pivotal for the development of individualized treatment plans, the optimization of surgical strategies, and the advancement of rehabilitative approaches for a variety of musculoskeletal and neurological disorders.

1.1 Conventional Approach

A conventional motion capture laboratory is an intricate configuration that includes multiple motion capture cameras, equipped for infrared or optical tracking affixed to stable structures. The image data acquired from the motion capture system is processed on high-performance workstations using specialized software. The individuals undergoing gait analyses are required to adhere reflective spherical markers to their bodies or don a special suit with markers attached to facilitate motion tracking [1]. Setting up a motion capture laboratory requires substantial investment and elaborate preparation due to the required specialized equipment and software [2] [3].

In contrast, emerging markerless motion capture technologies like Carecam leverage artificial intelligence and readily available devices for movement analyses. These technologies present a user-friendly and economically efficient alternative, offering significant advancements and greater accessibility to kinematic evaluation.

1.2 Carecam's Innovation

Carecam is an innovative tool poised to tackle and overcome the challenges and limitations in traditional motion capture, paving the way for novel advancements in the approach to movement analysis. Carecam employs novel methods allowing for markerless motion capture to track and record human or object movement without physical markers or sensors. This approach leverages computer vision, camera arrays, and depth sensors to capture and interpret movement using pose estimation (defined as the process of determining the position and orientation of an object or a set of key points on a subject). Carecam's solution uses video captured from a single consumer-grade camera to analyze a human subject's gait and does not require the subject to wear any wearables or have access to a motion capture laboratory, proprietary software, or expensive computer equipment.

Carecam uses advanced 2D and 3D computer vision, artificial intelligence (AI) algorithms, and custom-trained models to enable a single-camera solution for 3D movement analysis. This solution uses a single capturing device (e.g., an Apple iPad tablet) to generate highly accurate results. The principal objective of developing this technology is to increase access to kinematic data, improve precision in gait parameter quantification, validate the resultant outputs within a variety of clinical contexts, and enable the use of this technology globally in clinical settings and eventually at home.

2. 3D Gait Technology Overview

Gait analyses are used to study human motion to assess and treat individuals with conditions that impair their ability to walk normally [1]. Carecam is a universally accessible tool, poised to reframe the clinical landscape with a single-camera gait analysis tool offering precise and reliable insights into abnormal locomotion patterns and underlying pathophysiological conditions. Traditional systems for gait analysis often rely on expensive, specialized equipment, limiting their accessibility and usability [2] [3]. In contrast, by leveraging AI methods and a consumer-grade camera device, we can transform this technology into a widely available tool and expand adoption across multiple markets.

2.1 Primary objectives of 3D gait analysis

The primary aim of 3D gait analysis is to offer objective, actionable insights that improve patient outcomes and quality of life. Gait analyses are often used as a clinical diagnostic tool and to capture research data, fostering collaboration among healthcare professionals and scientists [4]. Carecam's approach emphasizes two key areas of gait analysis to achieve this goal:

- Optimizing adult neurological assessments and rehabilitation
- Optimizing movement for injury mitigation and performance enhancement

2.2 Adult Neurological Assessment and Rehabilitation

Effective rehabilitation of neurological disorders necessitates careful clinical assessments and consistent outcome tracking. Data-driven gait and movement analyses are pivotal in influencing rehabilitation strategies and treatment effectiveness [6]. However, due to the inaccessibility of large motion capture labs, clinicians often rely on subjective visual observations and patients' self-reports, potentially overlooking subtle abnormalities that may influence their management. Carecam's accessible technology offers an objective view of patient movement, identifying hard-to-detect motor dysfunctions, enabling earlier diagnoses, tailored interventions, and rehabilitation plans specific to the patient's needs.

2.3 Injury Mitigation and Performance Enhancement

The early detection of joint dysfunction identifies the susceptibilities to injury and the targeted, instructor-guided interventions enhance athletic performance [4]. However, challenges arise when delineating complex movements and transitioning proof-of-concept frameworks into functional real-world applications [4] [5]. Our technology uses an advanced pose estimation model to overcome these limitations, thereby democratizing gait analysis by rendering it more accessible and user-friendly for both patients and healthcare providers.

2.4 How Carecam Reforms Health Care

Carecam's technology leverages a single consumer-grade camera and advanced 3D image modeling algorithms to detect subtle motor dysfunctions, providing a deeper understanding of a patient's condition. This approach addresses the limitations of traditional methods and facilitates earlier diagnoses, more timely interventions, and a rehabilitation plan tailored specifically to the patient's needs.

2.5 Advantages of Single Camera Technology

The inclusion of single-camera technology in Carecam technology has several advantages for gait analysis applications.

- **Accessibility:** Single-camera technology is widely available and affordable, making it accessible to healthcare professionals, biomedical researchers, and individuals for home use.
- **Convenience:** Users can perform gait analysis in their natural environments without needing a dedicated lab or specialized equipment.
- **Real-Time Feedback:** This technology provides real-time feedback, allowing immediate adjustments in rehabilitation and performance training.
- **Privacy and Comfort**: This technology eliminates the need for markers, enhancing user privacy and comfort during gait analysis.

2.6 Clinical Impacts of Carecam's Approach

In clinical settings, this technology can be used to discern subtle deviations from normative values in step length, gait velocity, angles of movement, and cadence for conditions including Parkinson's disease and dementia and provide unique gait assessment data for individuals with stroke and other neurological conditions [5] [6] [7]. Carecam uses gait assessment parameters to help clinicians create personalized care plans by comparing patient data with benchmarks and tailoring the plans to individual patient conditions.

3. Intellectual Property of Carecam

Carecam's technology collects video using a single consumer-grade camera while the subject performs a 4-10m walk test or a Timed Up and Go (TUG) test [8]. In the captured video, the focus is on the person of interest (POI). As depicted in Figure 1, leveraging deep learning models, algorithms identify critical points in two dimensions (2D) on the POI, which are then extended to three dimensions (3D) for gait analysis. A comprehensive set of biomarkers are generated from these 3D key points. This approach integrates perspectives and methods from Computer Vision and Biomechanics to optimize the benefits of pose estimation technology.

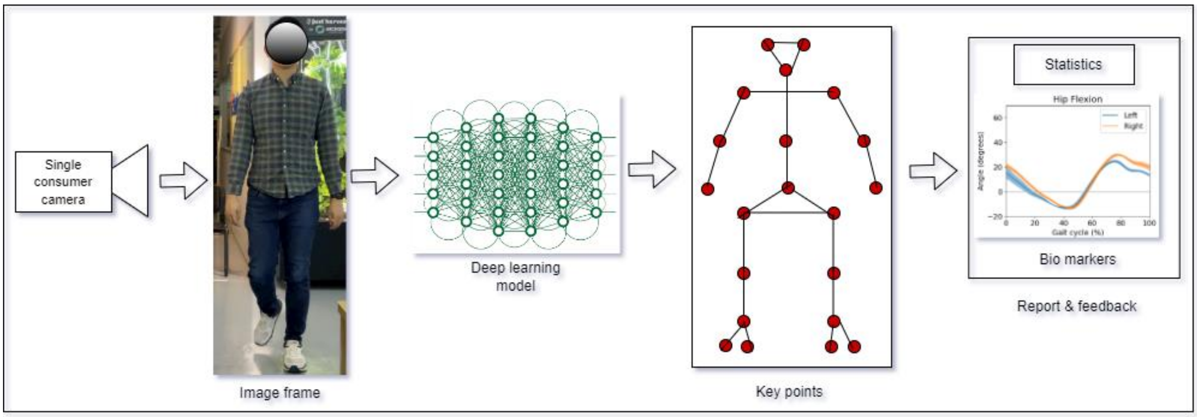

Fig. 1 This figure depicts a high-level end-to-end workflow of Carecam's technology.

4. Gait Biomarkers

Carecam's 3D Gait analysis produces more than 33 prominent biomarkers such as hip flexion, knee rotation, etc. A subset of these biomarkers is also included in the Gait Deviation Index (GDI) [9] to assess walking patterns in individuals with various musculoskeletal and neuromuscular conditions. Table 1 lists 33 biomarkers generated by Carecam's technology and included in the output report.

Table 1 List of biomechanical biomarkers

Name of biomarkers	
Pelvis Anterior Tilt	Pelvis Up Obliquity
Pelvis Internal Rotation	

Left Hip Internal Rotation	Right Hip Internal Rotation
Left Knee Internal Rotation	Right Knee internal Rotation
Left Ankle Rotation	Right Ankle Rotation
Left Hip Adduction	Right Hip Adduction
Left Shoulder Flexion	Right Shoulder Flexion
Left Elbow Flexion	Right Elbow Flexion
Left Hip Flexion	Right Hip Flexion
Left Knee Flexion	Right Knee Flexion
Left Ankle Dorsiflexion	Right Ankle Dorsiflexion
Left Ankle Inversion	Right Ankle Inversion
Stride Length	Step Length
Strides Per Min	Steps Per Min
Stride Duration	Step Duration
Left Foot Internal Progression	Right Foot Internal Progression
Single Support Time	Double Support Time

Discrete biomarkers (e.g., strides per minute, stride duration, etc.) are represented in an infographic form, while continuous biomarkers (e.g., pelvis rotation, knee flexion, etc.) are represented graphically as a function of the percentage of the gait cycle. Normal ranges for all biomarkers are provided to assist clinicians with interpretation.

5. Gait Analysis Report Overview

Carecam provides a comprehensive gait analysis report, which offers valuable insights into an individual's gait patterns and aids in the diagnosis and treatment of neurological and musculoskeletal conditions. Fig. 2 depicts a sample report generated from the Carecam 3D gait analysis approach. Each plot differentiates between left (blue) and right (orange) biomarkers and represents one gait cycle. The x-axis denotes the gait cycle (as a percentage) while the y-axis depicts the joint angle (in degrees). The concise information embedded in this report regarding a subject’s mobility facilitates informed decision-making about subsequent interventions.

5.1 Clinical Significance of Hip Related Biomarkers

The report includes flexion, adduction, and internal rotation of the hip (Fig. 3). These three gait parameters help clinicians identify an abnormality in the pelvis and the hip area. Limited hip flexion can indicate hip impingement, labral tears, or tight hip flexor muscles. Hip adduction plays a role in gait and balance. Assessing hip adduction can help diagnose problems related to the hip joint, pelvis, or lower back. Limited hip internal rotation can indicate various conditions, including hip labral tears, hip dysplasia, or muscle imbalances.

5.2 Clinical Significance of Knee Related Biomarkers

Knee flexion, adduction, and internal rotation (Fig. 4) allow clinicians to identify knee-related pathologies. Limited knee flexion can indicate problems such as knee joint stiffness, muscle tightness, or post-surgical restrictions. Assessment of knee adduction can be relevant in diagnosing conditions, including ligament injuries, joint instability, or patellofemoral pain syndrome. Clinically, assessing knee internal rotation is essential for diagnosing conditions such as meniscal injuries, ligament tears (e.g., ACL or PCL tears), or patellar tracking disorders.

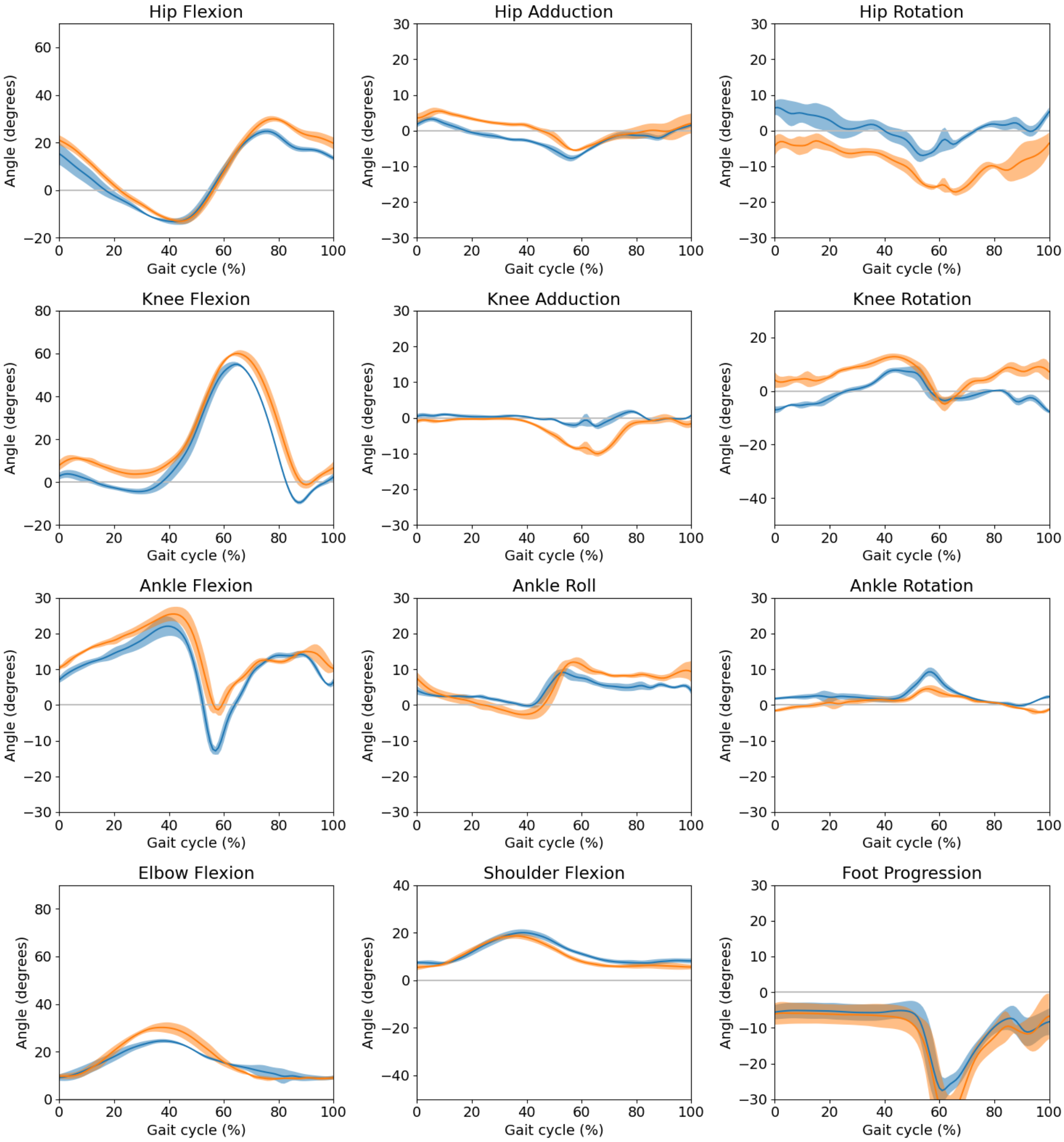

Fig. 2 An example of a gait analysis report generated from Carecam's approach

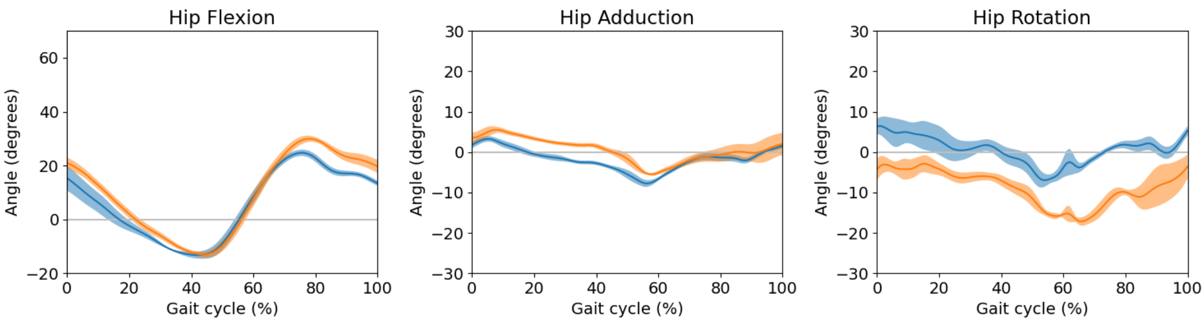

Fig. 3 A sample of gait analysis report of hip-related biomarkers.

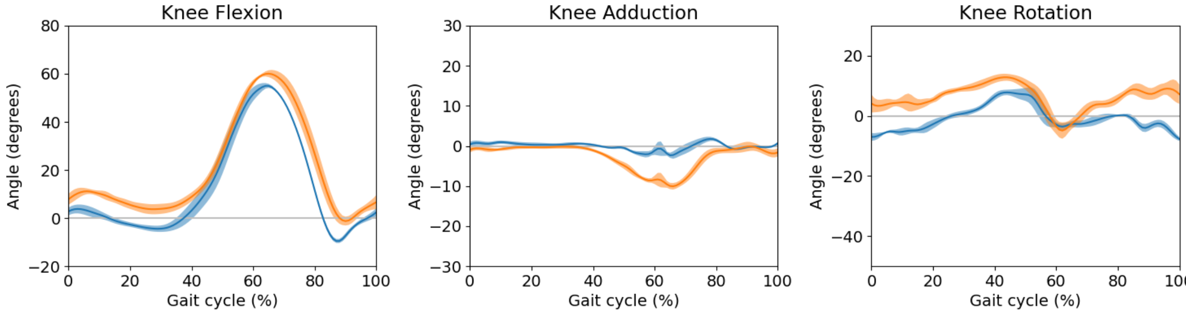

Fig. 4 A sample of gait analysis report of knee-related biomarkers.

5.3 Clinical Significance of Ankle Related Biomarkers

The ankle-related gait parameters (flexion, roll, and rotation) are shown in Fig. 5. Limited dorsiflexion can indicate problems such as Achilles tendon tightness, ankle joint stiffness, or calf muscle contractures. Reduced ankle flexion can be associated with issues like calf muscle injuries or ankle impingement. Clinical assessment of ankle Inversion and eversion is relevant for diagnosing and managing conditions such as ankle sprains, ligament injuries, or chronic instability. Excessive inversion can be a sign of ankle instability or instability-prone ligaments. The clinical relevance of ankle abduction and adduction lies in diagnosing conditions such as ankle impingement, posterior tibial tendon dysfunction, or pes planus (flatfoot) deformity. Limited abduction can be associated with issues like ankle joint restriction or tight ligaments.

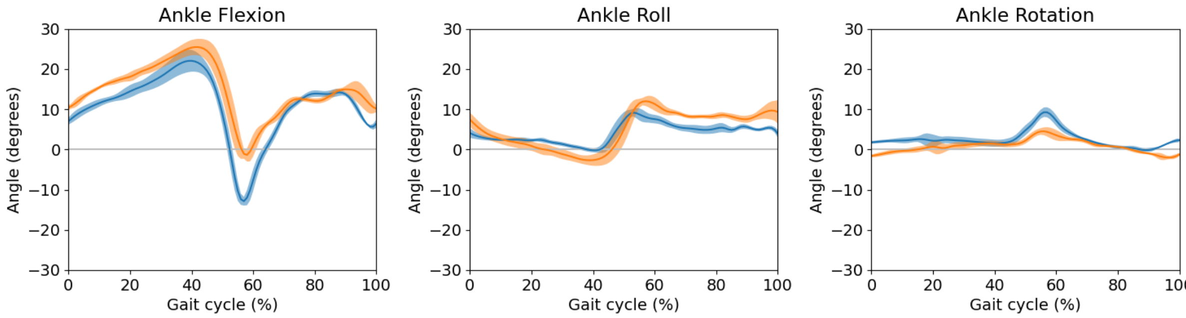

Fig. 5 A sample of gait analysis report of ankle-related biomarkers.

5.4 Clinical Significance of Elbow and Shoulder related Biomarkers or upper body biomarker

Elbow and Shoulder flexion provide information about the elbow and shoulder joint, respectively, and identify pathological conditions in those joints. Limited shoulder flexion can indicate various shoulder-related conditions or injuries, such as rotator cuff tears, adhesive capsulitis (frozen shoulder), or acromioclavicular (AC) joint disorders. Limited elbow flexion can indicate elbow osteoarthritis, ligament injuries, fractures, or contractures. Measuring the degree of elbow flexion helps diagnose and track the progress of these conditions.

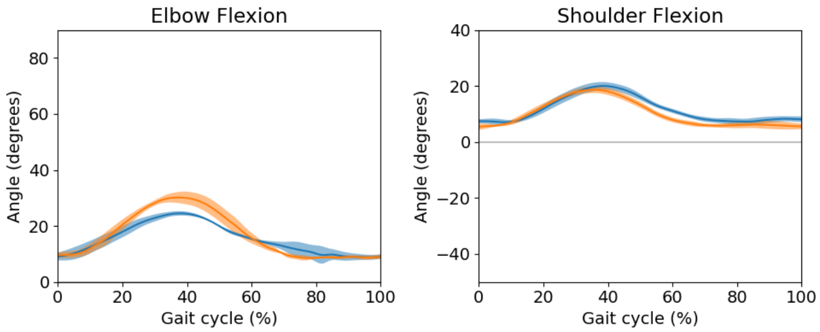

Fig. 6 A sample of gait analysis report of upper body-related biomarkers.

6. Comparison with Two Popular Markerless Motion Capture Systems

Carecam's capabilities were compared with two well-known Markerless systems: Method 1 (Table 2) and Method 2 (Table 3). Carecam's provides a simple, low-cost, practical, and user-friendly solution compared to the other existing methods. These features make its system ideal for large-scale use, especially in clinical and research environments where multi-camera setups might not be feasible and set it apart from other available markerless solutions.

Table 2 Comparison with Carecam's method with Method 1

Features	Carecam's method	Method 1
# Cameras and Tripods, Laptop/Server	1	2
Calibration of cameras	No	Yes
Synchronization of cameras	No	Yes
Analysis done on	iPad Pro	GPU Server
Internet connection needed	No	Yes
Report for comparison with prior trials	Yes	No

Table 3 Comparison with Carecam's method with Method 2

Features	Carecam's method	Method 2
Camera	1	6 to 8
Tripod	1	6 to 8
Calibration of cameras	No	Yes
Body-fitting clothing	No	Yes. Strict requirement.
Cost	$	$$$$
Export data usage	No special software	Visual3D
Portability	Yes	No
Works outdoors	Yes	No

7. The Future of Clinical Gait Analysis

With 3D gait analysis powered by AI on a single camera, clinicians can delve deeper into understanding human movement's intricacies. The precision and detail offered by 3D gait analysis using a tablet provide the ability to detect subtle motor dysfunctions that can drastically change the prognosis for many patients, allowing for earlier or more effective interventions.

7.1 Democratization of Healthcare

Apart from the evident clinical benefits, there is a bigger picture at play here - the democratization of healthcare. The combination of consumer-grade cameras and AI algorithms can allow advanced gait analysis to become more accessible and affordable to a larger segment of the population. Looking forward, the potential of this technology to revolutionize treatment methodologies and improve patient outcomes cannot be overstated. It promises a future where every patient receives personalized, data-driven care, optimizing their recovery journey.

7.2 AI-driven 3D Gait Analysis

AI-driven 3D gait analysis has immense potential, and its impact on health care is just beginning to be realized. The time has come for healthcare professionals, researchers, and institutions to embrace innovation, collaborate, and take the lead in ushering in a new era of rehabilitation and care. By harnessing the technology, we can explore new possibilities and Carecam become part of every patient’s journey.

References

[1] J. Perry and J. Burnfield, Gait Analysis: Normal and Pathological Function, United States: Trafford, 2010.

[2] M. McGrath, J. Wood, J. Walsh and P. Window, "The impact of Three-Dimensional Gait Analysis in adults with pathological gait on management recommendations," *Gait & Posture,* vol. sep, no. 105, pp. 75-80, 2023.

[3] M. Pistacchi, M. Gioulis, F. Sanson, E. De Giovannini, G. Filippi, F. Rossetto and S. Zambito Marsala, "Gait analysis and clinical correlations in early Parkinson's disease," *Functional Neurology,* vol. 32, no. 1, pp. 28-34, 2017.

[4] K.-K. Isabella, B. Andreas, W. Hannes, M. Janina, K. Inga and A. Peter, "Gait analysis – Available platforms for outcome assessment," *Injury,* vol. 51, pp. S90-S96, 2020.

[5] M. Molloy et. al., "Further evidence of validity of the Gait Deviation Index," *Gait & posture,* vol. 31, no. 4, pp. 479-482, 2010.

[6] T. Li et. al., "Automatic Timed Up-and-Go Sub-Task Segmentation for Parkinson’s Disease Patients Using Video-Based Activity Classification," *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* vol. 26, no. 11, pp. 2189-2199, 2018.

[7] A. Guzik et. al., "Relationship Between Observational Wisconsin Gait Scale, Gait Deviation Index, and Gait Variability Index in Individuals Poststroke.," *Archives of Physical Medicine and Rehabilitation,* vol. 100, no. 9, pp. 1680-1687, 2019.

[8] Y. Choi, Y. Bae, B. Cha and J. Ryu, "Deep Learning-Based Subtask Segmentation of Timed Up-and-Go Test Using RGB-D Cameras," *Sensors,* vol. 22, no. 17, pp. 1-23, 2022.

[9] M. Schwartz and A. Rozumalski, "The gait deviation index: a new comprehensive index of gait pathology," *Gait & Posture ;28:351–7.,* vol. 28, no. 35, pp. 1-7, 2008.