Accessible instrumented gait analysis in rehabilitation

Implementation of accessible instrumented gait analysis in the current care path in Basalt rehabilitation clinic The Hague

Master Thesis

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April 10, 2023

Thesis is partial fulfilment of the requirements for the joint degree of Master of Science in

Technical Medicine

Leiden University; Delft University of Technology ; Erasmus University Rotterdam
In collaboration with Basalt Revalidatie

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Preface

This master thesis research is executed in collaboration with Basalt rehabilitation The Hague and Technical University of Delft. This research combined with the clinical internship at Basalt The Hague, brought together all the components of what I think a student in Technical Medicine is thought to be: a researcher, an engineer, a physician and a project manager, bringing the technical and medical worlds closer together.

The internship at Basalt The Hague gave me the opportunity to grow in my clinical competences and in my self-assurance. I want to thank all therapists and nurses (and patients) of department 4.2 for their support and collaboration. I have never felt as welcome at an internship as at this department. Also, I want to thank all the A(N)IOSes (especially Yara van Boven) that thought me all the ins- and outs of rehabilitation medicine and included me within their group.

With regard to my research I want to thank Millanie de Bruijn and Elise Padmos, and the people of Livit orthopedics for their input of previous research and to set out the clinical requirements. Also I want to thank the volunteers of the tests for participating, without them there would not be any results. Special thanks goes to all the work and help provided by Martijn Stoker. Without him, the tests at Basalt Delft would not be possible.

This research would also not be possible without supervisors. I want to thank Paulien van der Meer and Ferrie Harberts for their guidance in the internship and the clinical aspects of the research. I want to thank Eline van der Kruk and Judith Cueto Fernandez for their knowledge and time, and for pushing me to dive deeper into this research. I want to thank Marjon Stijntjes for helping me manage the sometimes conflicting technical and medical worlds and for the support during the difficult moments of this thesis.

Finally, I want to thank my family and friends for their unconditional support and faith during this thesis and the road leading to it. I could not have done it without them.

Sanne van Deelen
Delft, April 2023

Summary

At Basalt rehabilitation clinic The Hague, gait analysis is currently mostly observational. No objective measures are used and there is no systematic use of recordings. The aim of this research is to find and verify an accessible instrumented gait analysis method that could be implemented in the current care path at Basalt The Hague. The current instrumented gait analysis systems are marker-based. Recently more research has been done with regard to markerless systems, since markers bring along artefacts like the soft-tissue artefact. Markerless systems work with pose detection through artificial intelligence. A limitation of these pose detection systems, is that it is still in a research phase and did not make its way into the clinics yet. In a comparison of the accuracy of open-source pose estimation methods for measuring gait kinematics, OpenPose has been found most accurate.

For this research a program of requirements is made for implementation of instrumented gait analysis in the clinic at Basalt The Hague. The coordinates of anatomical landmarks obtained with OpenPose are processed to kinematic parameters. Besides, spatiotemporal parameters are looked into. A gait analysis set-up (consisting of tripods and mobile phone cameras) with OpenPose is proposed and tested to verify the accuracy. The OpenPose outcomes are compared with the the Simi motion capture system at Basalt Delft. By determining the Pearson correlation coefficients between OpenPose and Simi motion capture system, the kinematic parameters are verified. The mean standard deviations of the repeated recordings with OpenPose are used to determine the repeatability of OpenPose.

With this research is verified that OpenPose is repeatable and that kinematic parameters of the hip and knee are highly correlated to the standard method of instrumented gait analysis used at Basalt. Therefore can be concluded that OpenPose pose detection seems a promising method for determining kinematic and possibly also spatiotemporal parameters of gait. With follow-up research, especially clinical validation, and further development of the data processing, the first steps can be made towards implementation of accessible instrumented gait analysis in the current care path at Basalt The Hague, and possibly other locations and/or institutions.

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List of Abbreviations

AFO	Ankle-Foot Orthosis
CI	Confidence Interval
CNN	Convolutional Neural Network
DGI	Dynamic Gait Index
EMG	Electromyography
FGA	Functional Gait Assessment
FOV	Field Of View
GALN	Ganganalyselijst Nijmegen
GARS	Gait Assessment Rating Scale
GRF	Ground Reaction Force
HRNet	High-Resolution Network
IR	Infrared
IWW	Interactive Walk-Way
LUMC	Leiden University Medical Center
MWT	Meter Walk Teset / Minute Walk Test
NCSRR	National Center for Simulation in Rehabilitation Research
PAF	Part Affinity Field
POMA-M	Performance-Oriented Mobility Assessment - Mobility
RGB	Red Green Blue light
ROM	Range Of Motion
SD	Standard Deviation
TSU	*Technisch Spreek Uur*
TUG	Timed Up and Go
2D	Two dimensional
3D	Three dimensional

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1 Introduction

Part of the patients admitted to a rehabilitation clinic have an impaired motor function. An impaired motor function influences a patient's walking pattern. Gait analysis is used to observe a patient's walking pattern and to determine the mechanisms of the musculoskeletal system. The outcomes of gait analysis are used for fitting orthoses, indicating botulin toxin treatment, indicating surgery on soft tissue, advising on therapeutic interventions and advising on physical therapy goals. [1] Within this research, gait analysis is split into two sub types: observational gait analysis and instrumented gait analysis. Observational gait analysis is the observation of a patient's gait by a clinician or therapist without the use of any cameras and joint detection methods. Instrumented gait analysis uses cameras and joint detection methods (with marker or markerless) to analyse a patient's gait. Currently gait analysis is mostly done by observational clinical assessment tools in the clinical setting.[2][3] The evaluation of these kind of clinical assessment tools is influenced by the observation and estimations of the clinician, and is therefore a subjective measure. Subjectiveness can be overcome by objective measuring through instrumented gait analysis. Research has proven that instrumented gait analysis improves the decision-making process of the treatment. [4][5] Instrumented analysis also provides the clinician with kinematic parameters that can not be obtained by observation, like displacement, speed, repeatability, etc. [6]

At the moment instrumented gait analysis is only done in a small number of clinics. Instrumented gait analysis is expensive and a time-consuming process. Therefore, only a relatively small group of patients are analyzed with the instrumented gait analysis. However, there is a need from the clinicians to perform instrumented gait analysis more often, to track a patients treatment effect with objective measures. The aim of this research is to find and verify an accessible instrumented gait analysis method that could be implemented in the current care path at Basalt Rehabilitation clinic The Hague. The report is set out as follows. First background information in human movement dynamics and current insights in instrumented gait analysis is provided. The methods section provides a program of requirements, an overview of the current care path and the clinical test setup for the video-based motion capture set-up that fits the program of requirements. The results provide the results of a pilot study to verify the chosen set-up. In the discussion the feasibility of instrumented gait analysis in the clinic is described and recommendations for future research are provided.

2 Gait analysis

The musculoskeletal system consists out of multiple interconnected components such as bones, muscles, ligaments and joints, and the interactions between them. Injury to one or more of these components influence the ability to move. The gait cycle is described by eight phases (see Figure 2). The ratio of standing phase and swing phase within this cycle is 60% and 40% respectively. The ground reaction force (GRF) describes the counter force of a mass on the ground form the center of pressure. The moments created by the GRF on the joints, depend on the magnitude of the GRF and distance between these joints and the GRF vector. [7] The principles of human movement dynamics are the basis for gait analysis.

Normal gait cycle

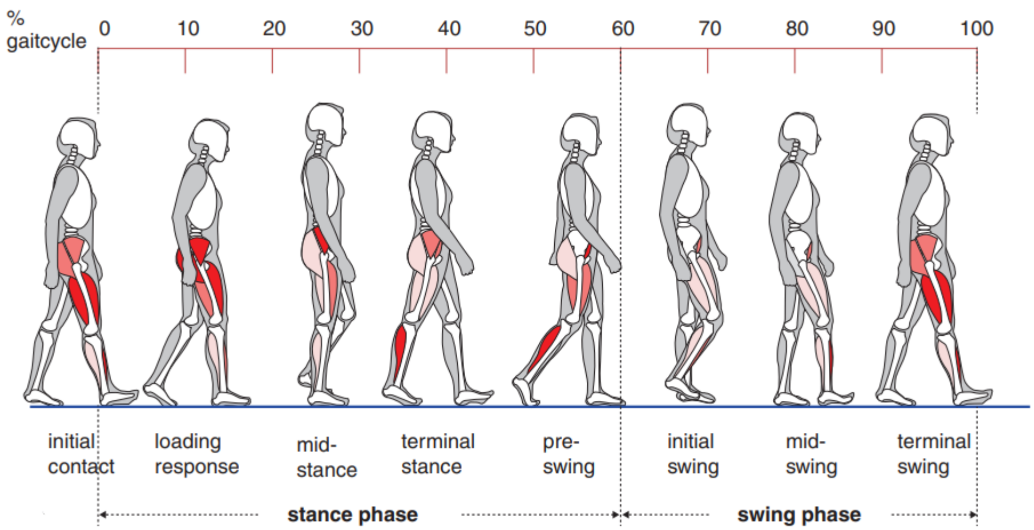

Figure 1: Positioning of the lower limbs in the phases of a normal gait cycle. [7]

Gait analysis is used to observe a patient's walking pattern and to measure the performance of the musculoskeletal system. With knowledge of human movement dynamics, deviations in the gait can be distinguished from normal gait. In clinical practice, gait analysis is often still done by observation. In research and some clinics also instrumented gait analysis is used. Different technologies are used within instrumented gait analysis. The main categories of differences in technology are the use of markers and the dimensions of the model (2D or 3D). Within gait analysis different parameters are obtained, which can be classified in the following categories: kinetic parameters (parameters related to forces, like joint moments and powers), kinematic parameters (parameters related to space and time, like joint angles and displacement) and spatiotemporal parameters (e.g. walking speed, cadence/steps per minute and stride length).[8] [9]

2.1 Observational gait analysis

Observational gait analysis can be done through observational tests. There are several types of walk-tests depending on how much the patient can be challenged and what information is needed for the treatment process. Walk tests are used to determine the endurance of a patient while walking. The test can be either distance- (5-meter-walk-test/5MWT or 10-meter-walk-test/10MWT) or time-based (2-minute-walk-test/2MWT, 6-minute-walk-test/6MWT or 12-minute-walk-test/12MWT). [10] The timed-up and go (TUG), lets a patient stand up from a chair, walk 3 meters, turn and sit down again. When the time of performing these tasks is prolonged, there is a higher fall-risk. [7] Another method is the *Ganganalyselijst Nijmegen* (GALN). This method analyses the range of motion during gait per body part (trunk, pelvis, hip, knee and ankle).[11][12] Similar to the GALN, the Rancho Los Amigos Observational Gait Analysis System observes the gait per body part. The system provides an overview of muscle activity, joint motion and kinetics, which is used to analyze gait abnormality and help with clinical decision-making.[13][14] The Dynamic Gait Index (DGI), often used with Parkinson, measures the risk of falling and the gait. During this assessment the patient is asked to walk in different ways (changing walking speed, obstacles, different positions of the head, etc.) Scores are given per walking situation and the total score informs about the patient's fall risk.[15] An altered version of the DGI is the Functional Gait Assessment (FGA). This method uses 7 of the 8 test-items of the DGI and 3 additional items specific to balance. [16] The Gait Assessment Rating Scale (GARS) is a scoring list looking into deviations in general categories (variability, waddling, etc.), lower extremity categories (foot contact, range of motion, etc.) and trunk, head, and upper extremity categories (arm-heelstrike synchrony, upper trunk flexed forwards, etc.) The total score ranges from normal to severely impaired gait.[17] Lastly, the Performance-Oriented Mobility Assessment - Mobility (POMA-M) or test of Tinetti, analyzes 7 characteristics of the gait and the existence of abnormalities: gait start, stride length/height, stride symmetry, stride continuity, trunk movement and distance between heels.[18][7] The parameters and outcomes from observational gait analysis tests found in literature can be found in Table 1.

2.2 Instrumented gait analysis

In order to overcome the subjectiveness issue with observational gait analysis, instrumented gait analysis can be used to obtain objective measures. Different systems with regard to instrumented gait analysis exist. The main differences in systems are presence (or absence) of markers and if the systems is based on 2D or 3D biomechanical models. All systems have their own advantages and disadvantages. A commonly used system for research and development of musculoskeletal models and dynamic simulations is OpenSim, created by the National Center for Simulation in Rehabilitation Research (NCSRR). OpenSim enables calculation of variables that are difficult to obtain with clinical assessments or instrumented measurements, as mentioned in the introduction. Besides, the models provide a tool to predict novel movements and human movement dynamics influenced by device interaction or surgery outcomes can be simulated. [19] Besides the main components of gait analysis, cameras and analysis software, additional measurements and materials can be added to the gait analysis. Systems can be used with force plates to determine the GFR, or with electromyography (EMG) to determine (the extent of) muscle contractions. Some systems also use treadmills (with integrated force plates), since the system does not move with the patient during gait.

2.2.1 Marker-based vs markerless

Instrumented gait analysis can be categorized in marker-based and markerless gait analysis. The clinics that use instrumented gait analysis, mostly use marker-based systems. The markers are placed on the joint landmarks which can be tracked on video during gait. However, using markers has limitations. First of all, issues can arise in model calibration. Which can be caused by inconsistent or incorrect placement of the markers by clinicians, or due to determination of joint centers in relation to the markers. Also, measurements with markers are influenced by soft-tissue artefacts. [20] Soft-tissue artefacts are caused by movement of the skin, and thus marker location, over the anatomical landmarks. [21] Lastly, accurate placement of markers can be a lengthy process, which makes it challenging to integrate in existing care paths. There are two different types of markers that can be used for marker-based motion capture systems. Active markers radiate a signal. Passive markers reflect visible or infrared light. Active markers can be assigned to individual identifiers, which make them easy to re-detect after occlusion. Passive markers can not be assigned to individual identifiers before data acquisition, therefore there is more marker confusion during occlusion. Systems which use passive markers fill in these marker gaps, for example by interpolating the data. [22][23]

Passive vs active markers

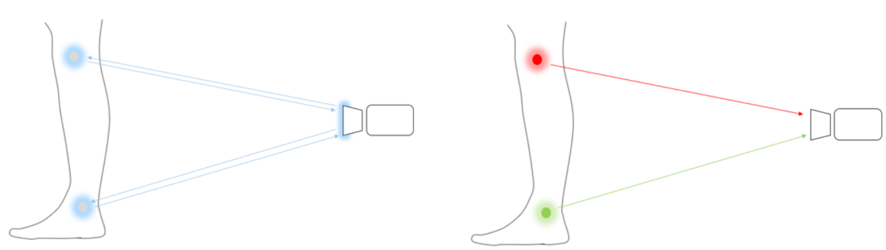

Figure 2: With passive markers (left) light (shown in blue) is transmitted from the camera system, and reflected from the marker back to the camera. Active markers (right) transmit their own (LED) light (shown in red and green) which is captured by the camera.

Observational parameters and outcomes

Parameter	Analysis test
Kinematics	
Contralateral drop pelvis	Rancho Los Amigos Observational Gait Analysis System [13]
Dorsiflexion ankle	Rancho Los Amigos Observational Gait Analysis System [13]
Elbow extension	GARS [17]
Forward/backward leaning trunk	GALN, Rancho Los Amigos Observational Gait Analysis System, GARS, POMA-M [11][13][17][18]
Head held forward	GARS [17]
Hip extension/flexion (ROM)	GALN, Rancho Los Amigos Observational Gait Analysis System, GARS [11][13][17]
Knee extension/flexion (ROM) / past retract	GALN, Rancho Los Amigos Observational Gait Analysis System, GARS [11][13][17]
Lateroflexion trunk	GALN, Rancho Los Amigos Observational Gait Analysis System [11][13]
Plantar flexion ankle	GALN, Rancho Los Amigos Observational Gait Analysis System [11][13]
Rotation pelvis	GALN [11]
Shoulder abduction	GARS [17]
Shoulder extension	GARS [17]
Shoulders held elevated	GARS [17]
Spatiotemporal	
Cadence	GALN [11]
Duration standing phase	GALN [11]
Stride length and height	POMA-M [18]
Variability	GARS, POMA-M [17][18]
Walking distance	2MWT, 6MWT and 12MWT [10]
Walking time	5MWT, 10MWT and TUG [10][7]
% time in swing	GARS [17]
Other	
Arm-heelstrike synchrony	GARS [17]
Being able to perform tasks during gait	DGI, FGA [15][16]
Degree of armswing	GALN [11]
Foot contact	Rancho Los Amigos Observational Gait Analysis System, GARS [13][17]
Foot drag (clearance)	Rancho Los Amigos Observational Gait Analysis System [13]
Gait start (hesitation)	POMA-M [18]
Guardeness	GARS [17]
Heel distance	POMA-M [18]
Heel off	Rancho Los Amigos Observational Gait Analysis System [13]
Staggering	GARS [17]
Stride symmetry	POMA-M [18]
Waddling	GARS [17]
Weaving	GARS [17]

Outcome	Analysis test
DGI	DGI, FGA [15][16]
GARS	GARS [17]

Table 1: Parameters and outcomes used in observational assessments of gait analysis. Outcomes are indirect derivatives of the parameters. The parameters are categorized in kinematic, spatiotemporal and other parameters. There are no kinetic parameters used in observational gait analysis.

To overcome the issues of markers in instrumented gait analysis, more types of markerless analysis systems are being developed. A way of markerless gait analysis is the Interactive Walkway (IWW). The system uses the Kinect V2 system for analysis of the walking patterns. Besides normal walking pattern, the IWW also looks into the person's ability to adapt to certain circumstances like avoiding obstacles, stops and turns. These adaptation assignments are included in IWW, since the adaptability can give information about the fall risks of a person. [24] The Kinect system is originally developed as a gaming controller. It uses RGB (red, green blue) and infrared (IR) cameras to detect a person. The detection is based in the time-to-flight principle, which means that distances are determined based on the time that it takes for the emitted light to travel to objects and back. [23] The Kinect system has been proven good in determining spatiotemporal parameters, but is limited with regard to kinematic parameters. [23][25] Another limitation of the Kinect V2 system, is that the software is no longer supported. The IWW is just a example of markerless gait analysis. Many researchers and companies are creating new biomechanical models which work without markers. Markerless gait analysis systems are often based on machine learning algorithms which are able to recognize joints and their movements. Examples of software using machine learning are: OpenPose, HRNet and OpenCap. OpenPose is an open-source 2D kinematic analysis tool, which determines kinematic and kinetic parameters by machine learning models. [26] OpenPose uses convolutional neural networks to determine confidence maps of the location and direction (Part Affinity Fields or PAF) of body joints in an image and uses this to match body parts to create a full body pose for the subject(s) in the image. [27] High-Resolution Net (HRNet) is a more recent developed classification network. Similar to OpenPose, HRNet creates heatmaps of the likelihood of body joints to be on certain locations in the image. [28][29]. OpenCap is a recently developed 3D human movement dynamics prediction system using smartphone videos. With inverse kinematics of OpenSim and deep learning models, kinematic parameters like joint angles can be determined. A physics-based musculoskeletal simulation approach is used to determine kinetics like joint moments and powers. OpenCap is able to predict muscle activation, joint loads and joint moments. [26] OpenCap estimates the GRF from the videos made. Pose detection in OpenCap is done by either OpenPose or HRNet. [30] A limitation of machine learning based systems is that there are often tested and trained on healthy people, which influences the generalizability.

2.2.2 2D vs 3D modelling

Instrumented gait analysis uses biomechanical models to reflect human movement dynamics. These models can be 2-dimensional or 3-dimensional. 2D systems are often less expensive than 3D systems, since they need less cameras, less complex analysis software and less time for measuring and analysis. Besides, often less expertise is needed for 2D analysis, since the results are less complicated. [31] Also, the fact that most of the time less materials (cameras) is needed for 2D systems, makes it portable. [32] A 3D analysis system, like the common used one from Vicon, uses a laboratory set-up with minimal 8 cameras, and thus requires a large and permanent available space. [22] The downside of using 2D systems instead of 3D, is that not all planes are taken into account, which makes that a non-parallel or far away plane could be exaggerated or distorted in the gait analysis. [32] For example, there is a higher risk on occlusion of the legs during gait with 2D compared to 3D gait analysis. [33]

3 Clinical practice

This report focuses specifically on implementation of accessible gait analysis in the clinic at Basalt rehabilitation The Hague. This means that the current (observational) gait analysis methods and the care paths around this are observed and taken into account for the program of requirements. The care paths within clinical rehabilitation (and outpatient clinic) of Basalt The Hague are mapped out to create an overview of the current workflow and how and where the new form of gait analysis could be implemented. Basalt The Hague works together with, among others, Basalt Delft and Leiden University Medical Center (LUMC). Both institutions have laboratory set-ups for instrumented gait analysis. These set-ups are looked into to see how instrumented gait analysis is used within the clinics and which pros and cons of these set-ups should be taken into account for the set-up in Basalt The Hague.

3.1 Care path

A patient that needs rehabilitation care has a specific help request with regard to limitations in their daily life due to a medical issue. A help request can be for example to improve the patient's ability to walk. Specialists (e.a. clinicians and physical therapists) will examine the patient and formulate a treatment plan. With regard to gait, treatment could be physical therapy, medical devices (e.a. orthoses) and/or botulin toxin. In a follow-up the effects of the treatment will be eaxmine, which can lead to either further or adjusted treatment, or that the solution for the patient's help request has been found. (see Figure 3).

General care path

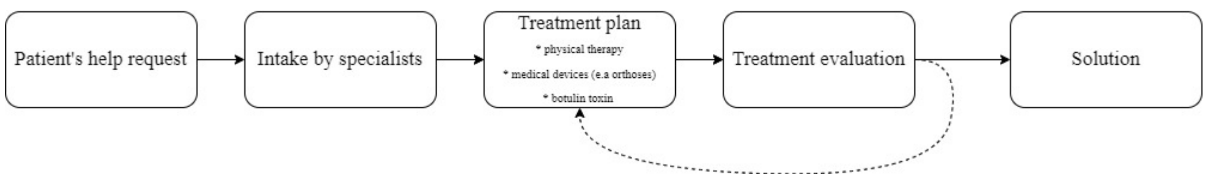

Figure 3: A patient's help request is examined by the specialists, who formulate a treatment plan to the help request. In a follow-up the treatment is evaluated, which can lead to either further or adjusted treatment (dotted line), or that the solution for the patient's help request has been found.

Currently, with regard to the patients in clinical rehabilitation a team of physical therapists, clinicians and medical instrument producers come together to observe the walking pattern of a patient with a help request with regard to their ability to walk on two moments of the week. These moments are called *technisch spreekuur* (TSU). Often no specific tests, like the ones mentioned in 2.1, are used. The walking patterns are simply observed by experienced specialists, looking at joint angles, clearance, walking speed, etc. The clinical care path is set out below.

The new proposed accessible instrumented gait analysis method needs to be fitted within the care path shown in Figure 3. If a patient's help request regards abnormal gait, the specialist should consider instrumented gait analysis from the intake to have a baseline measurement with objective measures. The results of the gait analysis should lead to a treatment plan. In a follow-up meeting, another gait analysis should be performed so that it can be compared with the baseline measures. Based on the changed objective measures and the patients opinion of the change in gait, the treatment plan can be evaluated. (see Figure 4)

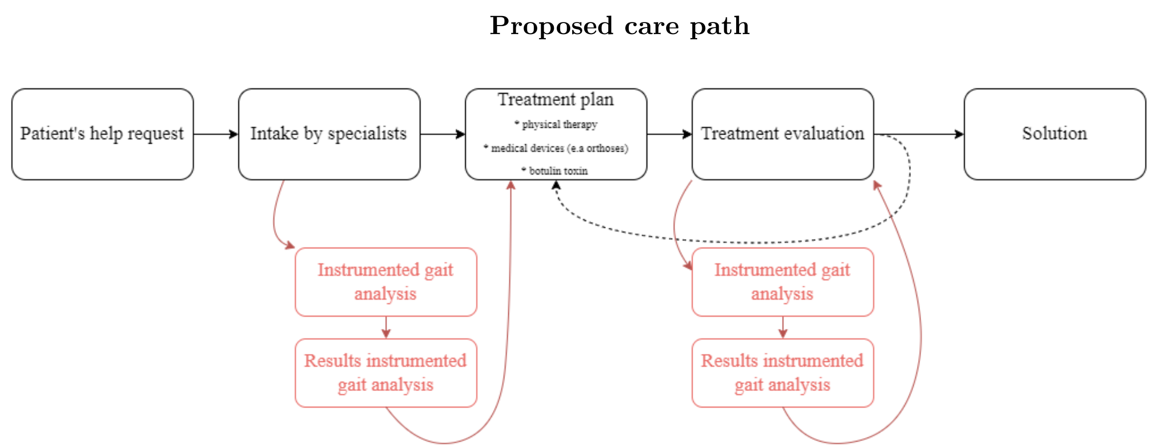

Figure 4: In red the implementation of the new proposed instrumented gait analysis can be seen. The results of the first instrumented gait analysis (made by the intake), form the baseline measures for comparison with the the follow-up analysis during treatment evaluation.

3.2 Instrumented gait analysis in the clinic

Patients of Basalt The Hague that require instrumented gait analysis are currently admitted for analysis in Basalt Delft. However, there is a limited capacity in analysis which can be done there, which causes a waiting list. Also, more frequent analysis, for example a follow-up of a patient before and after intervention, is not possible at the moment. Basalt Delft uses the 2D motion capture system of Simi reality motion systems for clinical gait analysis. The set-up consists of a walkway with a force plate and three cameras. Before measurement, the flexibility and spasticity of the lower extremities is determined with physical examination. The cameras are set-up in front, behind and one on a slider which is pushed along with the movement of the subject. The system can be used with passive and active markers. However, the passive markers are not used, since the bright light which is needed to light up the markers is found to be very uncomfortable for the subject and clinicians. The active markers are placed to determine the hip-, knee- and ankle angles, the range of motion (ROM). The force plate gives information about the strength and location of the ground reaction forces. Ideally, these GFRs are located in the direction of the joints. Often also EMG is used during the measurements, to determine (ab)normal activation of the muscles during walking. This activation can be altered in for example subject with spasticity. Important is also information from observation of the recorded videos. This gives information about unexpressed parameters like rotations in the joints, position of the upper body, take-off from the ground and distance between the foot and the underground. The limitations of this set-up are the fact that it is 2D and the general limitations of using markers.

LUMC recently started with 3D clinical gait analysis using the Vicon motion capture system. The set-up consists of multiple cameras for a 3D view of the subject, a treadmill with build-in force plates and option EMG. The Vicon system uses passive markers for detection of the joints. The force plates build within the treadmill measure the GFR with every step. The single force plate used in Basalt Delft only measures it for one step that ends up on the plate. In order to prevent falling, the subject should always be secured in a harness. EMG can also be included in this set-up. Unlike Basalt Delft, LUMC uses wired EMG, which can be uncomfortable for the subject. This set-up is able to detect similar parameters as the Basalt Delft set-up. However, since the measurements are done in 3D, more information is obtained about rotations of joints. Besides the limitation of the markers, additional limitations to this set-up is the harness, Possibly EMG wires, and the influence of the treadmill on the normal walking pattern.

4 Accessible instrumented gait analysis methods

Many researchers and companies are working on accessible instrumented gait analysis systems. An increasing amount of markerless models are created, based on artificial intelligence algorithms. Most of these models are tested on healthy people and not applied yet on patients in a rehabilitation clinics. The models remain mostly research set-ups and do not often make the step towards implementation within the clinics. This report aims to work towards implementation of these kind of models within the clinics. The gait analysis set-up should overcome the limitations of observational gait analysis and currently used instrumented gait analysis set-ups. Due to time-limitations, not all possibilities for accessible clinical gait analysis can be extensively researched. Therefore a commonly used and promising set-up is chosen from literature.

4.1 OpenPose

A commonly used gait analysis method within research is OpenPose. Also, in a comparison of the accuracy of open-source pose estimation methods for measuring gait kinematics, OpenPose has been found most accurate. [34] OpenPose is chosen as gait analysis method for this report.

As mentioned before, OpenPose uses convolutional neural networks (CNN) to determine confidence maps of the location and direction (PAF) of body joints in an image and uses this to match body parts to create a full body pose for the subject(s) in the image. [27] CNNs uses convolutional layers to create new images, feature maps, by filtering the original image. In OpenPose, CNN is used to give confidence maps on if a anatomical landmark is present in the image. After detection of the anatomical landmarks, they need to be associated with each other. PAF creates a vector between the different anatomical landmarks. In the case that there are multiple people within the image, bipartite matching is used to associate body parts. Since PAFs take into account position and orientation, false associations are prevented. [27] Figure 5 shows these principles behind OpenPose.

OpenPose has mainly been used on healthy people, outside a clinical setting. Rehabilitation patients with an altered gait, often use walking aids like walkers or crutches to be able to walk (safely). Little information is known about the influence of these aids on gait analysis, since the analysis methods are often tested on healthy people. With regard to the influence of walkers, no articles have been found. Articles using crutches in gait analysis conclude that the accuracy of OpenPose is not disturbed by the crutches. [35][36]. Also, using ankle-foot orthoses (AFOs) did not influence anatomical landmark recognition by OpenPose. [36]

Confidence maps and part affinity fields in OpenPose

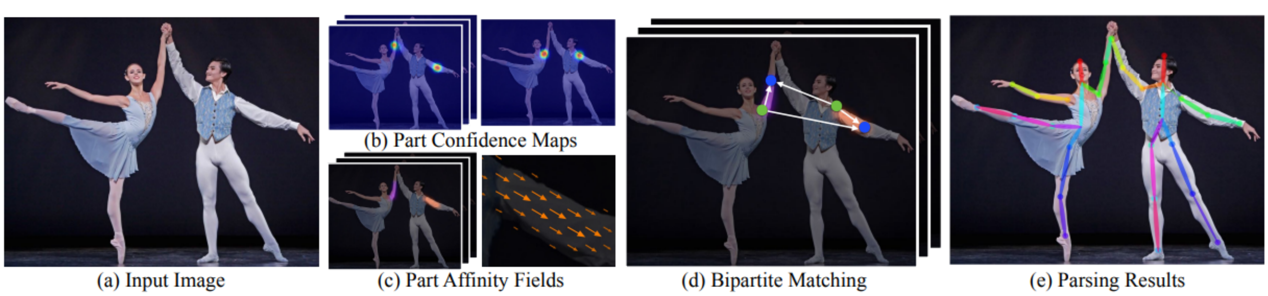

Figure 5: An input image (a) displays people (or a single person) in a certain position. In order to determine the pose of the people in the image the following steps are taken: confidence maps of the location of certain body parts are determained (b), then the part affinity fields (PAFs) creates a vector between body parts (c), by taking into account the position and orientation of the people, and lastly bipartite matching is used to associate body parts (d). All these analysis methods together form a pose detection model (e). [27]

OpenPose has two pose output formats: the BODY_25 model and the COCO model. The BODY_25 model consists of 25 keypoints, each reflecting a specific body part, whereas the COCO model consists of 18 keypoints (see Figure 6). [37] OpenPose is trained on recognising these keypoints based on a annotated data set. [27] With regard to rehabilitation, and gait analysis specifically, the BODY_25 model is better fitting since it also provides information about the positioning of the foot, and thus the angle of the ankle can be obtained. Also, the hips are reflected in three points (left-, right-, and mid hip) instead of two, which gives a better reflection of possible tilting in the hips.

OpenPose COCO and BODY_25 models

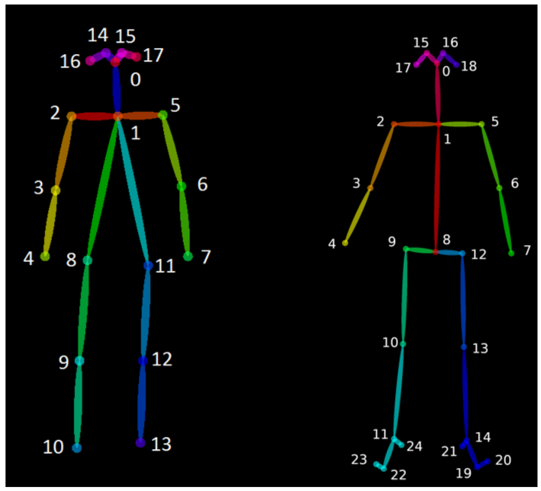

Figure 6: The COCO model (left) consists of 18 keypoints representing different body parts, the BODY_25 model (right) consists of 25 keypoints.

5 Methods

5.1 Program of requirements

A Program of requirements (see Table 2) is made based on the literature found about gait analysis, the current clinical process at Basalt The Hague and the input of clinicians. The requirements are categorized in general requirements, which are more institution and location bound requirements, and gait specific requirements, which are the specific objective parameters of gait.

Local data storage is a general requirement, since medical data should be protected due to privacy regulations. By using databases elsewhere, there is a higher risk of leaking medical data to other parties. Cost-efficacy is a requirement from the institution (Basalt Rehabilitation The Hague). The costs should be as low as possible to achieve implementation of new technology on short term. Also, the high costs of the laboratory set-ups of gait analysis is one of the most important limitations for implementation. Besides the cost-efficacy also space is a requirement specifically for the institution. The set-up within this research is based on the spaces available at Basalt Rehabilitation The Hague. However, since the set-up is based on a relatively small place and possibly not fixed, it easily adaptable to other places and institutions. The chosen gait analysis tool should also be generalizable. Which means that it should be applicable to many different rehabilitation patients. It should be applicable to different diagnosis, different gait patterns and with/without AFOs and/or walking aids. The gait analysis system will be used by specialists (clinicians, physical therapists, etc.). They should be able to use the system without extensive training. Therefore, things like a clear and simple user interface, and a clear overview of the results are important for implementation in the clinical processes. The system needs to be implemented with as little as possible change in the current clinical processes. The goal is to improve the current observational gait analysis by providing objective measures and not extending the clinical processes.

Specialists are asked what they would like to achieve with instrumented gait analysis in the clinic. General requirements that they would like to see are: being able to rewatch gait videos in slow-motion or frame-by-frame, and to be able to play videos of different situations (for example with or without AFO) next to each other, to compare the differences in gait pattern. Gait specific requirements (objective measures) that they would like to have are the joint angles of the hip, knee and ankle (especially in the saggittal plane), and spatiotemporal parameters like stride length and walking speed.

Program of Requirements

Requirement	Explanation
General requirements	
Local data storage	Due to privacy regulations, patient data should be stored locally
Cost-efficacy	Should be an inexpensive solution for day-to-day analysis.
Space	Should be a flexible set-up which require no permanent set-up, or a permanent set-up that fits within the current spaces without interfering with their current use.
Generalisable	Should be applicable to different patients with different abnormal gait patterns.
Usability	Should be easy in use to make the videos and to analyze/interpret the results without specific (technology) knowledge
Integration	Should fit within the current clinical processes.
Slow motion rewatch *	Looking at the videos frame by frame.
Comparison of videos *	Should be able to play videos of different situations (for example with or without AFO) next to each other, to compare the gait.
Gait specific requirements	
Joint angles *	Joint angles of the hip, knee and ankle help determine the 2D range of motion of these joints. Especially the angles within the sagittal plane.
Spatiotemporal parameters *	Parameters like stride length, walking speed, etc.

Table 2: Overview of the solution requirements. *requirements of therapists

5.2 OpenPose data processing

OpenPose provides a "stick man figure" simulating the movements of the subject. The BODY_25 model returns 25 keypoints that each represent a different a different body part: 0: Nose, 1: Neck, 2: Right Shoulder, 3: Right Elbow, 4: Right Wrist, 5: Left Shoulder, 6: Left Elbow, 7: Left Wrist, 8: Mid Hip, 9: Right Hip, 10: Right Knee, 11: Right Ankle, 12: Left Hip, 13: Left Knee, 14: Left Ankle, 15: Right Eye, 16: Left Eye, 17: Right Ear, 18: Left Ear, 19: Left Big Toe, 20: Left Small Toe, 21: Left Heel, 22: Right Big Toe, 23: Right Small Toe, 24: Right Heel (see Figure 6). The keypoints of an image or each frame in a video can be saved in a JSON-file ($--write-json$). In order to analyse the keypoints and to obtain kinematic and spatiotemporal data from the keypoint the keypoints data is processed in Python.

5.2.1 Kinematic parameters

After labeling the keypoints with the right body part, joint angles can be determined in the hip, knee and ankle with the following function (see Figure 7):

$$\emptyset = arccos(\frac{u \cdot v}{|u||v|})$$

Where u and v are vectors between the keypoints The hip angle is defined as the angle between the neck-hip vector and the hip-knee vector (for example for the right side, keypoints 1-9 and 9-10, in Figure 6), the knee angle is the angle between the hip-knee vector and the knee-ankle vector, and the ankle angle is the angle between the knee-ankle vector and ankle-toe vector. The angles are defined as a deviation from the neutral standing position, so the hip and knee angles are determined as deviation from 180°and the ankle position as deviation from 90°.

Joint angle calculation

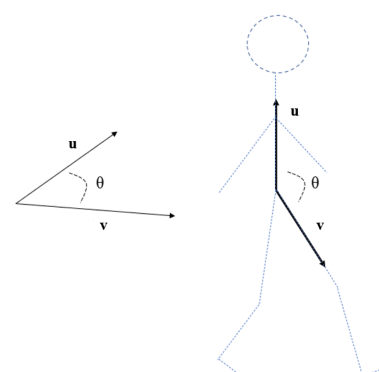

Figure 7: Visual representation for joint angle calculations. The u and v vectors each represent a body part and $\emptyset$ the angle between them. For example: u is the upper body and v the upper leg, thus $\emptyset$ is the hip angle.

The ankle angle can be determined by the knee-ankle vector and the ankle-toe vector. Several keypoints could be used to describe the vectors to calculate the ankle angle: ankle, heel, big toe and small toe. Initially, the ankle and big toe keypoints seemed most logical since it uses the keypoints on the turning point (ankle keypoints) and the main take off point of the foot (big toe keypoints). However, looking at the marker placement of the Simi motion capture system (which will be discussed later at 5.3.2), other keypoints or a combination of coordinates of the keypoints might give a better estimation of the ankle angle. Since it is unclear which keypoints will give better estimations, the ankle angle is determined with vectors between the following keypoints: (1) vector between the ankle keypoints and the big toe keypoints, (2) vector between the x-coordinates of the ankle and y-coordinates of the heel with the keypoints of the big toe, and (3) vector between the x-coordinates of the ankle and y-coordinates of the heel with the keypoints of the small toe. When using the y-coordinates of the ankle keypoints, an estimated offset of 10°is added to the 90°baseline position (which makes the ankle angle the deviation from 100°instead of 90°).

The joint angles measured with OpenPose and a stationary camera, are then adjusted for influences of OpenPose inaccuracies and of the camera(position). Adjustments are made based on comparison with outcomes of Simi motion capture system at Basalt Delft (which is described in more detail later, in 5.3.2). This system is, partly due to the use of markers (as mentioned in subsubsection 2.2.1), not flawless, but since it is the standard method to objectify kinematic measures at Basalt, this system is used for comparison of the potential new gait analysis set-up with OpenPose. The outcomes from OpenPose are obtained with a frame rate of 30 frames per second. The outcomes of Simi motion capture have a frame rate of 50 frames per second. In order to be able to compare then, the OpenPose joint angles are interpolated to a frame rate of 50 frames per second. The hip and ankle (of the xankle/yheel-big toe vector) are corrected for a linear offset in the joint angles. By determining the mean of the joint angle signal, a linear slope can be seen instead of an expected horizontal graph. The cause of the linear offset remains unclear, but since it clearly improves the baseline within the graphs of the hip angles, linear correction is implemented. The linear offset is distracted from the original join angle graph.

After correction of the hip and ankle angles, for all joint angles outliers are removed to prevent disruption of the filtering which will be applied afterwards. Outliers are removed with a cut-off value for unrealistic values of gait angles during gait. Afterwards the joint angle data from all measurements, OpenPose with moving or stationary camera (see 5.3.2) and the Simi motion capture system, are interpolated to fill in any gaps within the data. Then, the data is filtered with a 4th order 6Hz lowpass butterworth according to literature. [38] A digital filter is applied which moves forward and backward over the signal to prevent lag in the filtered signal.

In clinical practice, kinematic parameters are often shown in gait cycles. A gait cycle measures from the moment of initial contact of a foot to the following moment of initial contact of the same foot. During initial contact, the hip is in maximal flexion. Therefore, the maximum peaks of the hip angles are used to cut the measurements in gait cycles. Before selecting the peaks, the signal is filtered with a 4th order 2Hz lowpass butterworth filter, to smooth the peaks and prevent detection of noise as peaks. The filter is only used for peak detection, not for presenting the data in gait cycles afterwards. The data shown in gait cycles is filtered with the 4th order 6Hz lowpass butterworth filter as mentioned before. Expressing gait cycles in percentage of the total gait cycle allows the possibility to describe the possible deviations of gait in phases of gait: 0-10% loading response, 10-30% mid stance, 30-50% terminal -stance, 50-60% pre swing, 60-73% initial swing, 73-87% terminal swing and 87-100% mid stance. [7] The gait cycle is presented in a relational line plot, giving the mean of the joint angles of a collection of gait cycles and the 95% confidence interval for each measurement point.

Gait cycle phases

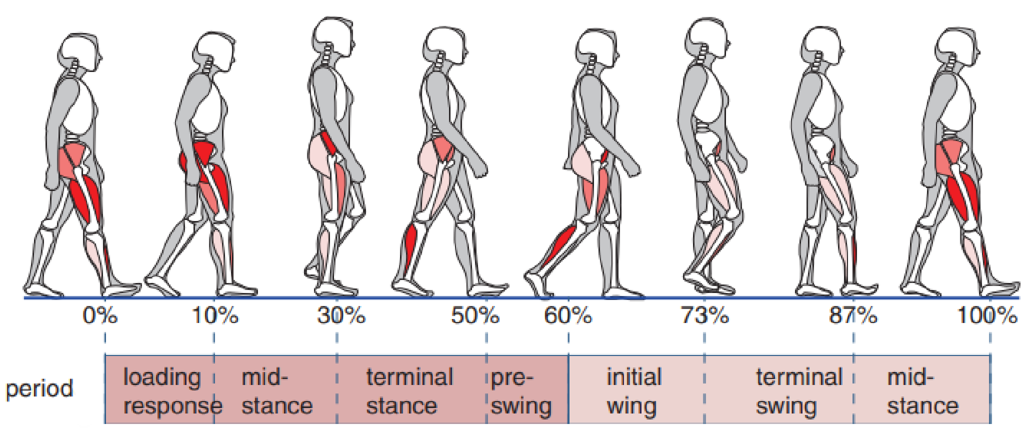

Figure 8: One gait cycle from initial contact to initial contact with the same foot, and the phases of the gait cycle.[7]

5.2.2 Additional: Spatiotemporal parameters

Besides the kinematic parameters, also spatiotemporal parameters can be determined with instrumented gait analysis. Within this research the focus was on the kinematic paramters obtain through OpenPose. The first steps are made towards estimation of the spatiotemporal parameters with the OpenPose data, but needs further testing and development.

Stride is defined as the distance between consecutive point of initial contact of the same foot. Step is the distance between initial contact point of the one foot and the one of the other foot (see Figure 9). [39] The stride distance is found by analysis of the x-coordinate of the heel. During the swing phase, the x-coordinate changes, during stance the heel remains on the same spot. The distance between each stance moment, is the stride of the concerning leg. The difference between the stance phases of the two different legs is used to determine the step length. The difference between the minimal and maximal y-coordinates of the heel and toe are used to determine heel- and toe clearance. The spatiotemporal parameters can be expressed in meters by translation of the coordinates to meters. Since the videos are cut from starting to end of the 5 meter walkway, the first heel to the last heel coordinates are an estimation of the walkway length in coordinates. Therefore an estimation can be made of the parameters in meters. The spatiotemporal and kinematic parameters are both expressed in relationship to the frame number. The frame number is converted to time, by using the frame rate of 30 frames/second.

Stride vs step

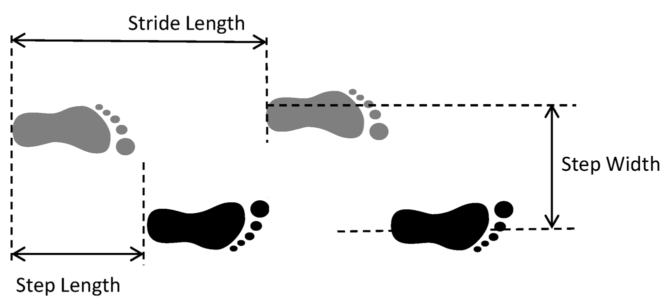

Figure 9: Stride is defined as the distance between consecutive point of initial contact of the same foot. Step is the distance between initial contact point of the one foot and the one of the other foot. [39]

5.3 Pilot study: verification of OpenPose

The overall goal of this research is to find and verify a low-cost and simple method to objectify gait analysis in a rehabilitation clinic. Specifically focused on the implementation at Basalt rehabilitation The Hague. A first step towards this goal is through a pilot study that explores the verification of the chosen gait analysis method: OpenPose. A larger research with more research participants and clinical validation can be performed if the pilot study shows promising results. Gait analysis with OpenPose will be tested in multiple phases. Phase 1 is to determine the right set-up and to develop and improve data processing of the positional gait information obtained by OpenPose. Phase 2 is to compare the OpenPose set-up with the standard instrumented gait analysis method of Basalt, with the Simi motion capture system at Basalt rehabilitation Delft (see subsection 3.2). Phase 1 and 2 will both be peformed with healthy participants. The criteria which the participants need to fulfil can be seen in Table 3.

The test set-up (see Figure 10) consists of a 7 meter walkway (consisting of a 5 meter walkway with 1 meter marks before and after this walkway) and two mobile phones on tripods. A 5 meter walkway is chosen based on the walking test with the least distance, so the 5MWT. 10MWT takes up too much space. The 1 meter marks before and after the 5 meter walkway is to exclude start up and slow down from the 5MWT. Based on literature search on the usage of OpenPose for gait analysis, a distance of minimal 2 meters from the subject seems best. Based on the available space at Basalt rehabilitation The Hague, a distance of 2.5 is used for the sagittal view. The height of the phone camera's is about 1 meter. The aim is to have a central view of the full body of the subject. Since the height of subjects differ and changing the height of the tripods with every subject takes time and can be forgotten, a standard camera height is more convenient in clinical practice. [40][34][41][42][43]

Criteria test participants

Healthy group
Two legs
Ability to walk
No known injuries or conditions that influence the gait
Adult (18+ years)

Patient group
Two legs
Ability to walk at least 10 meters
Adult (18+ years)

Table 3: Criteria which the healthy and patient participant groups need to fulfill.

Schematic test set-up

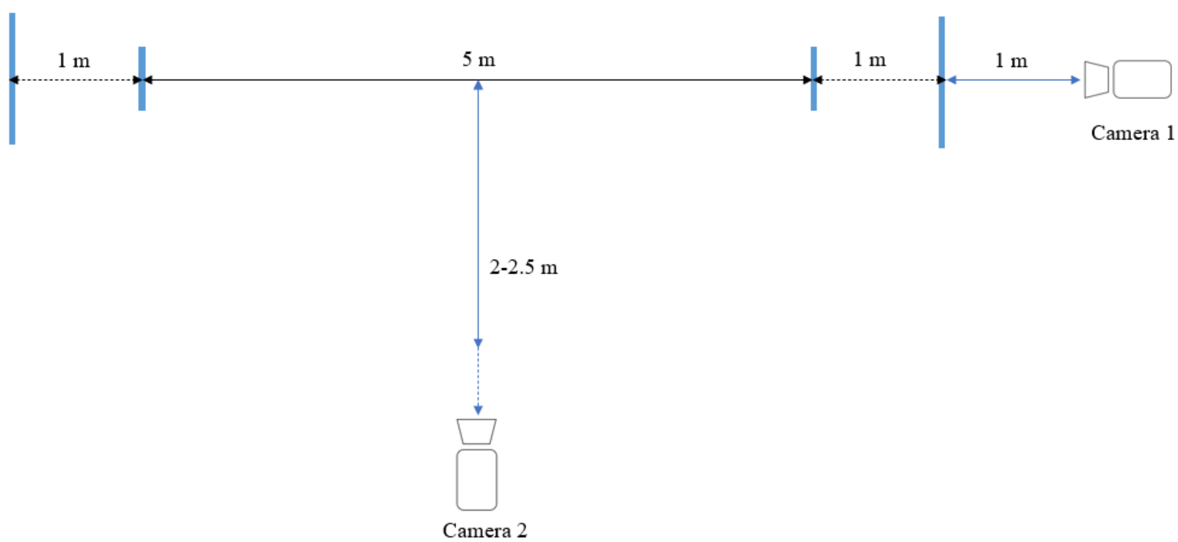

Figure 10: Test set-up plan of a 5 meter walkway with 1 meter extension on start and end. Camera 1 provides videos of the frontal view and camera 2 the sagittal view. The sagittal camera needs a minimum distance of 2 meters. Based on the available space at Basalt The Hague (see Figure 11) this distance can be extended to 2.5 meters.

The test set-up uses 2 the same tripods and 2 mobile phones. The frontal view is recorded with a Samsung Galaxy S8 and the sagittal view with a Samsung Galaxy A20e (see section 8 for camera specifications). The phones are chosen on availability during the research. The mobile phone used for the sagittal view, has a wide view camera. By using the wide view, the resolution of the camera decreases from 13 to 5 megapixels. The wide view camera has a field of view (FOV) of 123°. If the 5 meter walkway needs to be exactly within this FOV, the cameras should have a distance of at least 1.36 meter from the subject ($(5/2)/tan(123/2) \simeq 1.36$). So, placement of the camera on 2-2.5 meter distance from the subject as mentioned in the methods, captures the whole 5 meter walkway.

5.3.1 Phase 1: test at Basalt The Hague

At Basalt the Hague a room normally used for physical therapy is chosen for the gait analysis set-up. This room has the available space and is normally already used for TSU. The cameras should be placed in the room, so that the light from the windows comes from the back of the sagittal camera (to prevent backlight) and with the frontal camera on the same side of the mirrors (to prevent disturbance by the movements seen in the mirror) (see Figure 11). For the tests at Basalt The Hague, participants are asked to walk the 7 meter walkway once in their own normal gait speed. The participants can wear their own clothes and shoes, except clothes that disturb the participant's (for example a long doctors coat).

Set-up at Basalt The Hague

Figure 11: Set-up in the physical therapy room at Basalt The Hague. 1 and 2 show the placement of the phone cameras on tripods. The blue arrow is the 7 meter distance lines which the subjects have to walk. The white arrow shows the 5 meter distance which is recorded and analysed.

5.3.2 Phase 2: test at Basalt Delft

The tests at Basalt Delft are used for testing repeatability of OpenPose in combination with the data processing, for comparison with the Simi motion capture system and for testing the influence of "assistance" in the form of an extra person walking with the participant on the joint detection by OpenPose. The recordings are made in the designated gait analysis room at Basalt Delft. At Basalt Delft, normally a walkway of 7.25 meter is used for the gait analysis. Since this is close to the 7 meter walkway chosen for the test set-up (see Figure 10), and to prevent confusion of walkway markings for the participants, it has been decided to use the 7.25 meter walkway. Similar to the test-setup, within the 7.25 meter walkway a 5 meter walkway has been marked for sagittal analysis with recordings of the tripod camera. The set-up at Basalt Delft can be seen in Figure 12). The tripods with cameras are placed within the FOV of the moving sagittal camera and frontal camera of the Basalt Delft set-up. By doing a test running the two systems at the same time, it was concluded that the disruption of the tripods within the recordings made with the moving sagittal camera were minimal. Blocking the FOV and thus detection of the markers resulted in a small gap in the data from the Simi motion capture system. The placement of the frontal tripod camera in front of the frontal camera from Basalt Delft had no consequences, since these recordings are not analysed with the Simi motion capture system. The frontal camera is only used for observational gait analysis.

Set-up at Basalt Delft

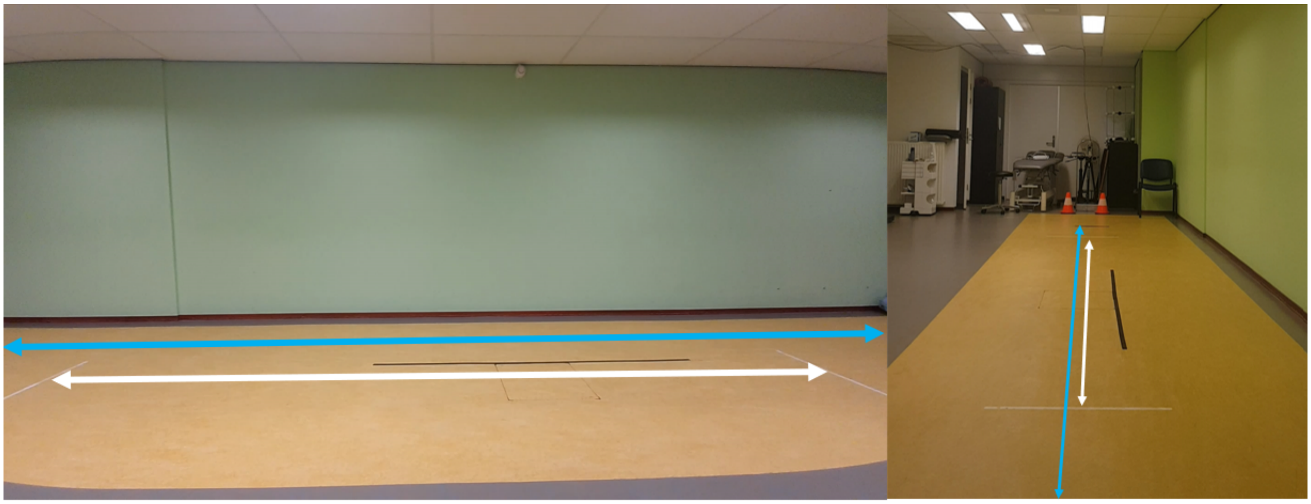

Figure 12: Set-up in the gait analysis lab at Basalt Delft. The left image shows the sagittal view from the tripod camera. The right image shows the frontal view of the tripod camera. The blue arrow is the 7.25 meter distance lines which the subjects have to walk. The white arrow shows the 5 meter distance which is recorded and analysed.

As mentioned before in 3.2, the Simi motion capture system at Basalt rehabilitation Delft uses active markers for determining the joint angles. The markers are placed in the same way it is normally placed for gait analysis, not taking into account the OpenPose detection points. It is chosen to not change anything with regard to the Simi motion capture system, in order to maintain the normal practices and thus to compare also with the standard measurements at Basalt. The marker placement can be seen in Figure 13. The markers are placed on the femur, knee joint, and on the foot. The kinematic outcomes are the femur-, knee- and ankle angle. At Basalt Delft the standard method is to measure the femur angle is measured instead of the hip angle, since the hip angle is determined by both the position of the upper leg and the position of the pelvis. The position of the pelvis is difficult to determine since the position of the upper body does not always correlate with the position of the pelvis. The femur marker is placed in the mid-line of the upper leg. How high up on the upper leg does not matter, as long as it is placed along the mid-line. The joint angle is determined from the vector between the knee and foot marker and the vector between the two foot markers. The foot markers are placed as close as possible to the ground, creating a straight line parallel to the ground. The foot marker closest to the heel is placed in a straight line through the mid-line of the lower leg and the lateral malleolus. The markers are placed on the foot and not on the ankle joint itself since placement on the ankle joint will give more plantar flexion than in reality. This is caused by the angle offset of the vector between a marker on the ankle joint and the marker on the foot. During the test, participants will walk both ways, so both legs can be recorded and measured. Therefore, markers are placed on both legs. Before performing the tests with the participants, it has been tested if the markers did not disturb the pose detection algorithm of OpenPose. No disturbance was seen in this test run.

During these tests, the participants will be recorded and analysed by the Simi motion capture system and the OpenPose system with data processing. Since the Simi motion capture system requires markers, the participants are asked to partake the tests in underwear or shorts. It has been chosen to perform these tests on bare feet, since this is more common for gait analysis than with shoes. The markers are placed by each participant by the same experienced gait analyst at Basalt Delft, to limit variability in marker placement. For the same reason, the moving camera is pushed by the same gait analyst each time. Since the recordings will be used for determining repeatability and to have more data for comparison with just a limited amount of participants, the participants are asked to walk up and down the walkway three times. The cameras are not stopped in between walking down the walkway each single time, since this has no influence on the recording and tests, and takes less time for the participant and gait analyst. Also, three of the participants perform a second recording set (once up and down the walkway), walking together with a second person. This last test is performed to determine if OpenPose is able to distinguish two people walking close to each other, in order to see if assistance for people with a risk of falling is possible, and thus to establish the patient population for gait analysis through OpenPose.

Marker placement

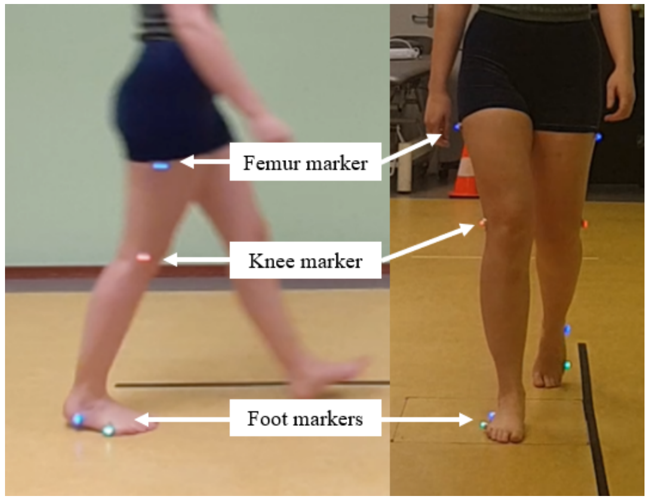

Figure 13: Placement of the active markers of the Simi motion capture system at Basalt Delft.

The outcomes of the Simi motion capture system are collected within a textfile with the following data: time in seconds, tibia in-declination in degrees, femur angle in degrees, knee angle in degrees, ankle angle in degrees and the x and y coordinates of the markers. Similar as described in 5.2 the angles are described as a deviation from neutral, so 0°for the femur, 180°for the knee and 90°for the ankle angle. OpenPose produces JSON-files containing the 25 keypoints (x and y coordinates) of joints and other anatomical keypoints as mentioned in 5.2. The outcomes of the Simi motion capture system en OpenPose (using a stationary and moving camera) are processed following 5.2 and analyzed for verification of the OpenPose set-up.

5.3.3 Data Management Plan

For this pilot study, recordings and joint coordinates of healthy participants are collected. During the research, the results are stored and processed on a personal laptop, and backed-up on the project drive of TU Delft. Data obtained with the systems of Basalt will also be backed-up at the local storage of Basalt Delft. After the research, the data can be accessed for follow-up research by TU Delft and/or Basalt. Access can be granted by the supervisors of this research connected to the TU Delft. All results are processed anonymously within this report. The participants give consent to use the recordings and joint coordinates for this and follow-up research by signing a informed consent.

5.3.4 Analysis

For verification of the OpenPose set-up, the outcomes using a stationary and moving camera are compared with the outcomes of the Simi motion capture system of Basalt Delft. The outcomes are compared using the Pearson correlation coefficient. To verify the occurrence of discrepancies between the systems, an plot can be made of the error (difference between the system outcomes) in each gait cycle. Based on these comparison outcomes, a judgment can be made on the accuracy of the OpenPose set-up. Besides the accuracy, also repeatbility of the OpenPose set-up is important with regard to verification of the proposed methods for gait analysis. It is important for the reliability of the set-up that the outcomes are always the same. Repeatability is tested by comparing the kinematic outcomes of the 3 repeated recordings of a single side of each participant. The participant will walk in their normal gait pattern in all the recordings under the same circumstances. There will always be small deviations due to the fact that someone never walks exactly the same and with the exact same speed. However, these deviations should be minimal. By plotting the gait cycles, the influence of gait speed is eliminated. A measure of repeatability is the standard deviation. The standard deviation says something about the dispersion of the data. The standard deviation is calculated for each point within the gait cycle. The gait cycles of all three recordings of the same participant from the same side are combined in this analysis. To determine the standard deviation over the whole gait cycle, a mean standard deviation is calculated.

6 Results

6.1 Testing kinematic parameters

For the tests taking place at Basalt Delft (phase 2), a total of 5 participants (N=5) performed the tests described in 5.3.2. For each participant the normal gait pattern is recorded three times for both the right and left side. This means that of 5 participants 3 times 2 sides are recorded, which sums up to 30 recordings. Besides, 3 participants are recorded walking with "assistance" for both sides. This provides 6 additional recordings. The participants, of which 3 female and 2 male, are all 20-25 years old. During processing the first 6 recordings of participant 1, failure of one of the markers was detected. The active marker accidentally turned off during the recordings, which causes missing data with regard to the Simi motion capture data. Therefore, recording 5 was unusable and recording 3 is missing information about the ankle angle. To compensate for the missing data 2 extra recordings were made walking with a normal gait pattern.

6.1.1 Comparing OpenPose with Simi motion capture systems

Example screenshots of te OpenPose pose detection and Simi motion capture can be seen in Figure 14. OpenPose outcomes are obtained from the recordings with the tripod camera (recording from a single fixed location) and the raw videos of the moving camera which are used for analysis with Simi motion capture. An example of the 3 different outcomes (Simi motion capture system, OpenPose with a moving camera, and OpenPose with an tripod camera) can be seen in Figure 15. Other outcomes can be found in the Appendix. The accuracy of OpenPose compared to the standard way of testing, with the Simi motion capture system at Basalt Delft, is expressed in Pearson correlation coefficients (see Table 4 for the unfiltered data and Table 5 for the filtered data). Within this table, the average correlation coefficients per person per side are given. The correlation coefficients and P-values per recording can be seen in the Appendix.

Simi motion capture and OpenPose pose detection

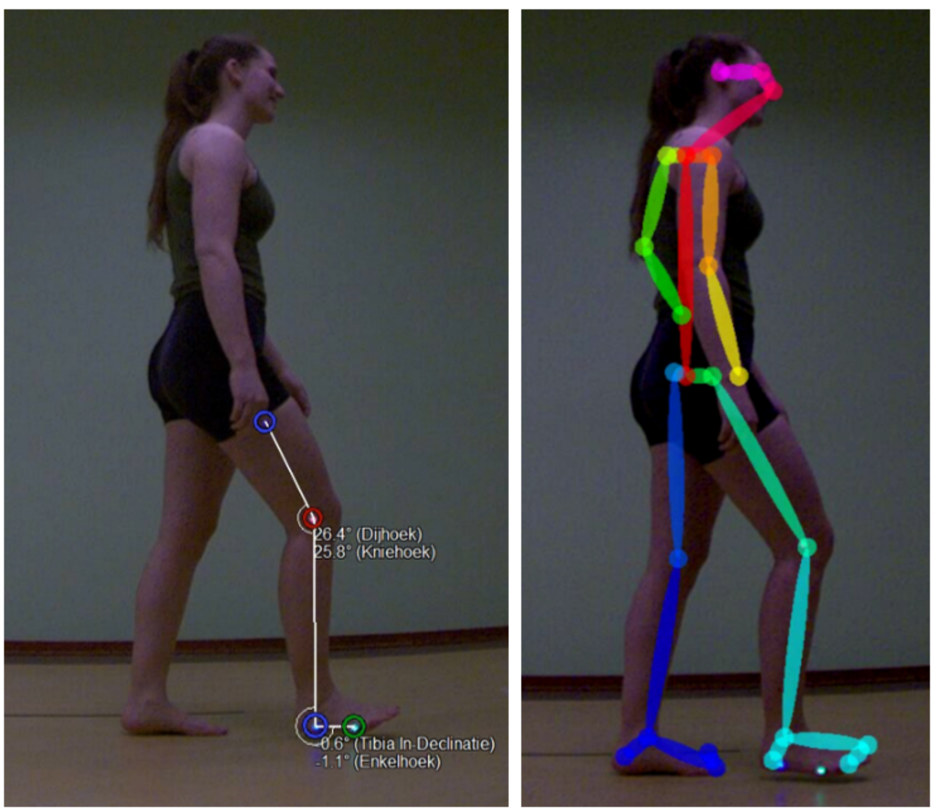

Figure 14: Example screenshots of pose detection by Simi motion capture (left) and OpenPose (right).

Correlation Simi motion capture and OpenPose

Participant	**Side**	**Joint angle**	**Simi vs moving** average correlation	**Simi vs tripod** average correlation	**Moving vs tripod** average correlation
1	Left	Hip	0.97	0.81	0.80
		Hip[1]		0.89	0.87
		Knee	0.99	0.96	0.95
		Ankle[2]	0.74	0.72	0.65
		Ankle[3]	0.83	0.78	0.70
		Ankle[4]		0.78	0.70
		Ankle[5]	0.77	0.52	0.44
	right	Hip	0.97	0.88	0.85
		Hip[1]		0.96	0.94
		Knee	0.98	0.94	0.93
		Ankle[2]	0.70	0.65	0.39
		Ankle[3]	0.77	0.73	0.65
		Ankle[4]		0.77	0.68
		Ankle[5]	0.72	0.75	0.69
2	Left	Hip	0.95	0.79	0.78
		Hip[1]		0.88	0.85
		Knee	0.99	0.88	0.88
		Ankle[2]	0.63	0.35	0.53
		Ankle[3]	0.82	0.57	0.59
		Ankle[4]		0.57	0.59
		Ankle[5]	0.79	0.32	0.35
	Right	Hip	0.95	0.85	0.80
		Hip[1]		0.95	0.91
		Knee	0.98	0.97	0.96
		Ankle[2]	0.54	0.46	0.43
		Ankle[3]	0.65	0.67	0.56
		Ankle[4]		0.69	0.59
		Ankle[5]	0.54	0.54	0.55
3	Left	Hip	0.96	0.85	0.81
		Hip[1]		0.94	0.90
		Knee	0.99	0.97	0.94
		Ankle[2]	0.65	0.31	0.51
		Ankle[3]	0.79	0.68	0.60
		Ankle[4]		0.69	0.62
		Ankle[5]	0.76	0.52	0.38
	Right	Hip	0.90	0.79	0.79
		Hip[1]		0.90	0.91
		Knee	0.95	0.89	0.91
		Ankle[2]	0.56	0.41	0.40
		Ankle[3]	0.69	0.69	0.62
		Ankle[4]		0.71	0.65
		Ankle[5]	0.66	0.70	0.68

Participant	**Side**	**Joint angle**	**Simi vs moving** average correlation	**Simi vs tripod** average correlation	**Moving vs tripod** average correlation
4	Left	Hip	0.97	0.73	0.72
		Hip[1]		0.77	0.76
		Knee	0.99	0.92	0.94
		Ankle[2]	0.50	0.10	0.31
		Ankle[3]	0.71	0.34	0.43
		Ankle[4]		0.36	0.44
		Ankle[5]	0.67	0.33	0.31
	Right	Hip	0.97	0.85	0.86
		Hip[1]		0.91	0.90
		Knee	0.99	0.90	0.89
		Ankle[2]	0.78	0.42	0.30
		Ankle[3]	0.83	0.67	0.56
		Ankle[4]		).70	0.59
		Ankle[5]	0.78	0.69	0.59
5	Left	Hip	0.97	0.81	0.81
		Hip[1]		0.88	0.87
		Knee	0.99	0.95	0.94
		Ankle[2]	0.59	0.33	0.49
		Ankle[3]	0.75	0.53	0.55
		Ankle[4]		0.55	0.55
		Ankle[5]	0.69	0.45	0.45
	Right	Hip	0.84	0.69	0.78
		Hip[1]		0.74	0.91
		Knee	0.93	0.90	0.95
		Ankle[2]	0.71	0.72	0.65
		Ankle[3]	0.75	0.77	0.73
		Ankle[4]		0.78	0.74
		Ankle[5]	0.63	0.73	0.72

Table 4: Average Pearson correlation coefficients between Simi motion capture system at Basalt Delft and OpenPose over a moving camera and a stationary camera on a tripod. ([1] with linear correction of the hip angles, [2] using ankle and big toe coordinates, [3] using yheel-xankle and big toe coordinates, [4] with linear correction of the ankle angels using yheel-xankle and big toe coordinates, and [5] using yheel-xankle and small toe coordinates.

Correlation Simi motion capture and OpenPose: Filtered data

Participant	**Side**	**Joint angle**	**Simi vs moving** average correlation	**Simi vs tripod** average correlation	**Moving vs tripod** average correlation
1	Left	Hip	0.98	0.94	0.92
		Knee	0.99	0.97	0.97
		Ankle[1]	0.80	0.81	0.77
		Ankle[2]	0.81	0.68	0.61
	Right	Hip	0.97	0.97	0.96
		Knee	0.99	0.97	0.96
		Ankle[1]	0.74	0.79	0.61
		Ankle[2]	0.75	0.76	0.75
2	Left	Hip	0.97	0.95	0.94
		Knee	0.99	0.96	0.95
		Ankle[1]	0.67	0.70	0.68
		Ankle[2]	0.83	0.59	0.68
	Right	Hip	0.96	0.96	0.93
		Knee	0.99	0.98	0.98
		Ankle[1]	0.62	0.75	0.62
		Ankle[2]	0.60	0.57	0.64
3	Left	Hip	0.97	0.97	0.94
		Knee	0.99	0.98	0.98
		Ankle[1]	0.72	0.73	0.78
		Ankle[2]	0.80	0.66	0.54
	Right	Hip	0.92	0.91	0.94
		Knee	0.95	0.93	0.97
		Ankle[1]	0.58	0.75	0.65
		Ankle[2]	0.72	0.72	0.75
4	Left	Hip	0.97	0.86	0.85
		Knee	0.99	0.99	0.98
		Ankle[1]	0.57	0.53	0.42
		Ankle[2]	0.72	0.63	0.61
	Right	Hip	0.98	0.91	0.90
		Knee	1.00	0.96	0.96
		Ankle[1]	0.83	0.81	0.78
		Ankle[2]	0.81	0.79	0.77
5	Left	Hip	0.98	0.96	0.95
		Knee	0.99	0.96	0.96
		Ankle[1]	0.67	0.57	0.51
		Ankle[2]	0.74	0.64	0.67
	Right	Hip	0.84	0.86	0.94
		Knee	0.93	0.92	0.97
		Ankle[1]	0.78	0.81	0.79
		Ankle[2]	0.69	0.75	0.81

Table 5: Average Pearson correlation coefficients between Simi motion capture system at Basalt Delft and OpenPose over a moving camera and a stationary camera on a tripod, with filtering of the OpenPose data. ([1] with linear correction and filtering of the ankle angels using yheel-xankle and big toe coordinates, and [2] with filtering using yheel-xankle and small toe coordinates.

Kinematics comparison

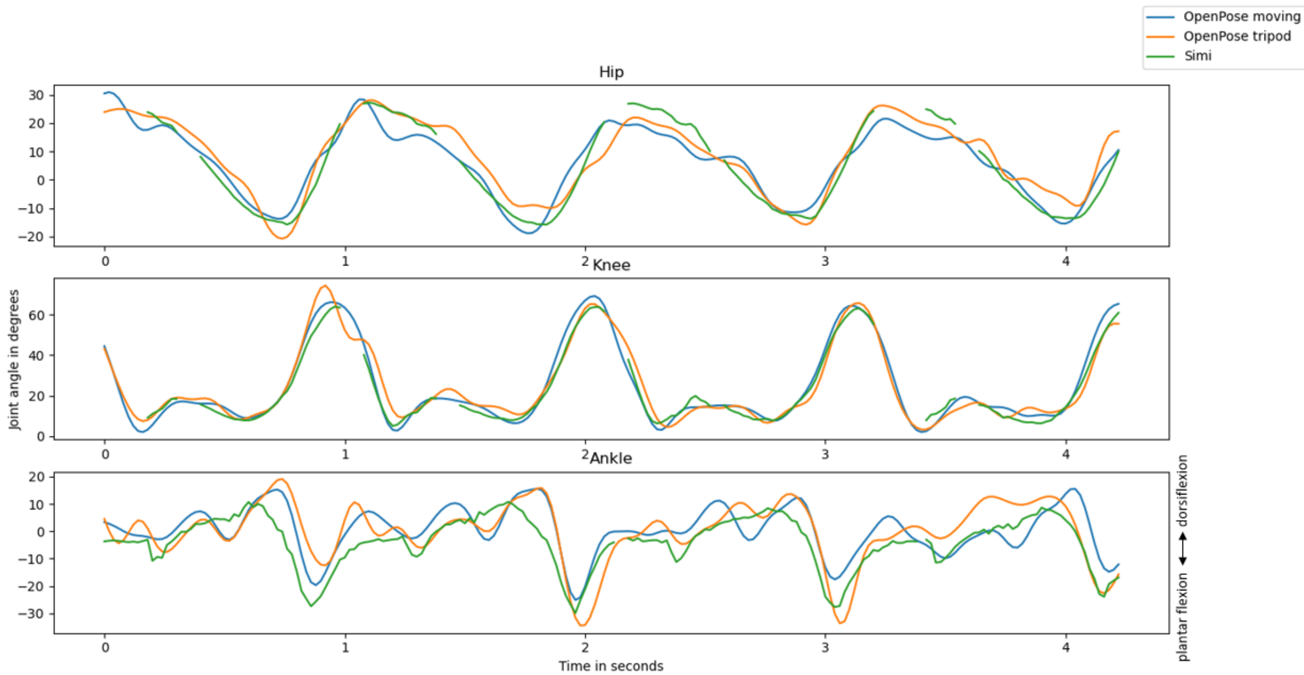

Figure 15: Example of kinematic outcomes determined with Simi motion capture, OpenPose with a moving camera and OpenPose with a camera on a tripod. The OpenPose outcomes are filtered with a 6Hz lowpass filter. In this graph the ankle angles of the OpenPose outcomes are measured with the vector between the coordinates of the big toe and the combination x-ankle with y-heel.

Figure 15 shows an example of the outcomes of this research. Most parts of the angles look similar like this example, with a few exceptions. Kinematic output plots of recordings with lower correlation coefficients in Table 4 and Table 5 (and the separate correlation coefficients in section 8 are observed to detect possible discrepancies that cause the lower correlation coefficients. With these observations the following categories of errors are distinguished: (1) errors at the start and end of a recording, (2) errors occuring mostly around the middle of the recording, and (3) errors consisting of a spike (see Figure 16). These errors have influence on the confidence intervals, which can be seen in Figure 17. In this example an type 2 error is seen within the angle plots of the ankle. The knee and hip do not show significant discrepancies. This results in relatively narrow confidence intervals of the hip and knee angle measurements and wide confidence intervals of the ankle angles. No patterns have been recognised in errors (the difference between the gait cycles of Simi motion capture and the gait cycles of the OpenPose analysis) within certain phases of the gait cycle.

Types of errors in comparison analysis

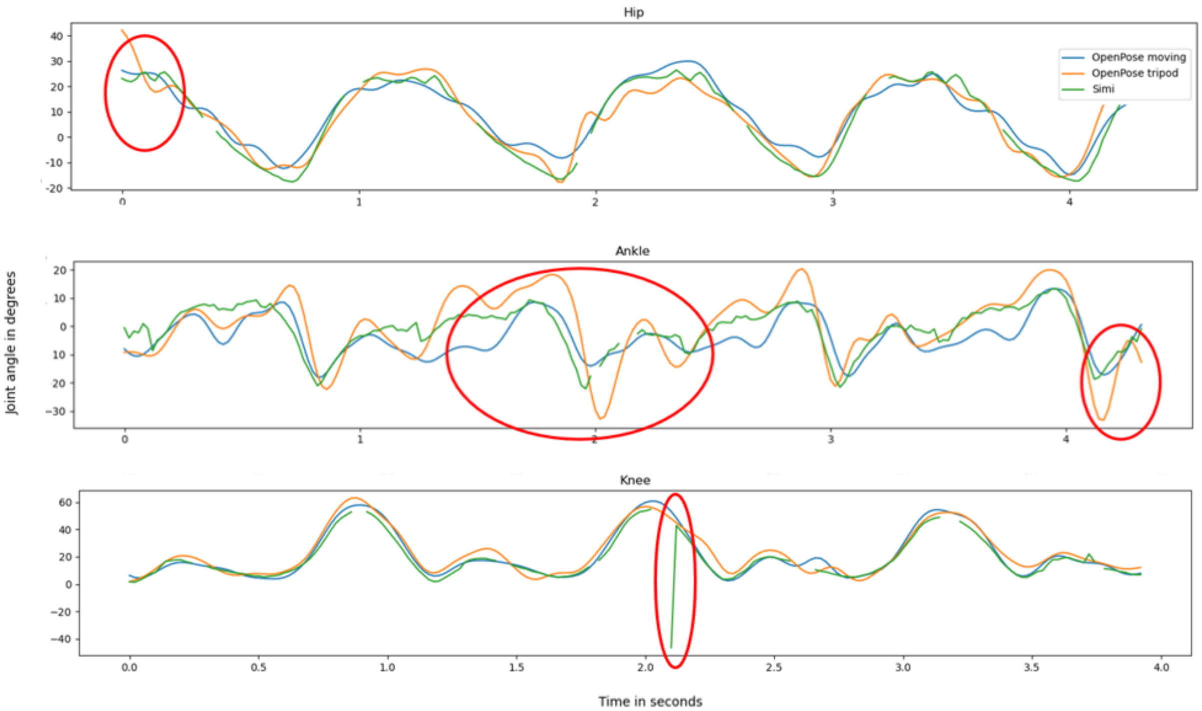

Figure 16: The top and middle graphs show type 1 errors at the start and end of a recording. The middle graph also shows a type 2 error around the middle of the recording. The bottom graph show a type 3 error, a spike.

Gait cycle errors

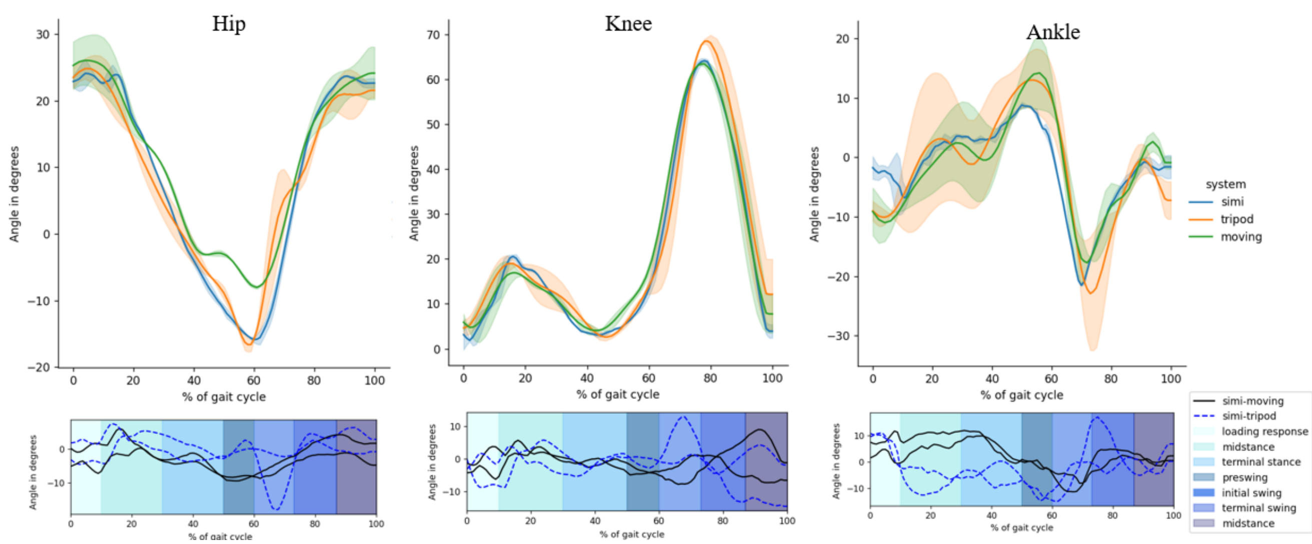

Figure 17: The top graphs show the joint angles of the hip, knee and ankle in gait cycles measured with Simi motion capture, OpenPose with stationary camera on a tripod and OpenPose with moving camera. The gait cycles are presented with a mean and 95% confidence interval over all gait cycles within the 5 meter walkway measurements. The bottom graphs show the error per gait cycle for the OpenPose set-ups compared to the Simi motion capture system.

6.1.2 Repeatability of OpenPose

Repeatability of OpenPose is tested by combining the repeated recordings of a participant. Figure 18 shows an example of the combined gait cycles of the three recordings of the same side of a single participant. Also the standard deviation per data point is plotted within the gait cycle graph. The mean standard deviations of each side of each participant can be found in Table 6. Fluctuations in mean standard deviation are seen at the right ankle of participant 1 and left hip, knee and ankle of participant 4. The deviations are caused by errors as mentioned in 6.1.1.

Repeatability analysis

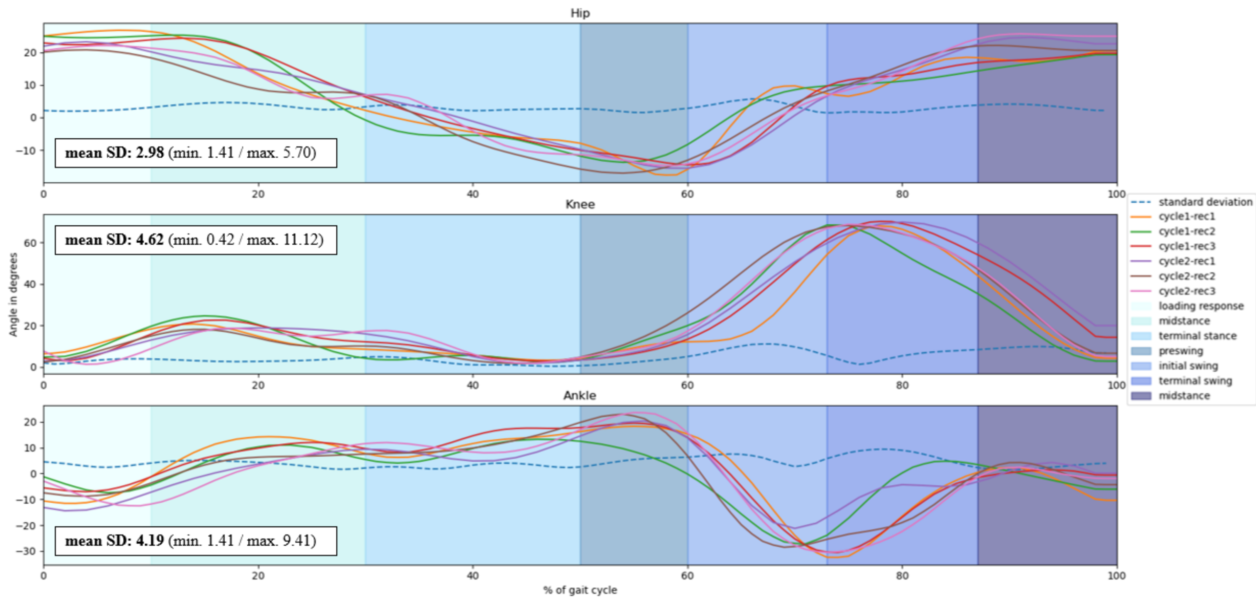

Figure 18: The colored lines represent the gait cycles within the 3 recordings of the same side of a single participant. The standard deviation during this gait cycle is given by the dotted line. Also, the mean standard deviation (SD) over the whole gait cycle is given, together with the minimum and maximum standard deviation.

Mean standard deviations OpenPose recordings

Subject	**side**	**Hip** *mean SD (min/max)*	**Knee** *mean SD (min/max)*	**Ankle** *mean SD (min/max)*
1	left	2.98 (1.41/5.70)	4.62 (0.42/11.12)	4.19 (1.41/9.41)
	right	2.60 (1.29/3.89)	4.97 (1.26/10.39)	6.26 (2.74/11.63)
2	left	2.73 (1.26/4.73)	3.54 (0.92/9.41)	4.41 (2.10/7.36)
	right	2.36 (0.83/3.76)	5.02(1.69/7.41)	4.13 (1.58/7.41)
3	left	2.91 (0.86/4.17	3.99 (0.60/9.85)	4.32 (1.74/8.16)
	right	2.88 (1.39/4.51)	3.89 (0.20/10.59)	4.25 (0.83/9.46)
4	left	7.06 (2.86/19.36)	5.83 (1.57/14.22)	7.39 (3.04/11.98)
	right	3.06 (1.10/6.68)	4.12 (1.18/10.53)	4.36 (1.57/9.66)
5	left	2.17 (0.70/4.86)	4.21 (0.95/13.48)	4.54 (1.48/7.18)
	right	3.04 (0.72/5.17)	4.67 (0.67/8.80)	3.68 (0.39/8.03)

Table 6: Mean standard deviations over the three recordings per measurement.

6.1.3 Influence of second person in frame

As mentioned in 5.3.2 three participants performed a additional test walking with a person in order to determine if OpenPose can distinguish a second person within the frame which is walking close to the participant. The Simi motion capture system detects only the movements of the participant, since it only detects the markers. The outcomes can be seen in Figure 19 and Figure 20. As can be seen, the OpenPose signal contains a lot of noise, making the normal angle pattern unrecognisable.

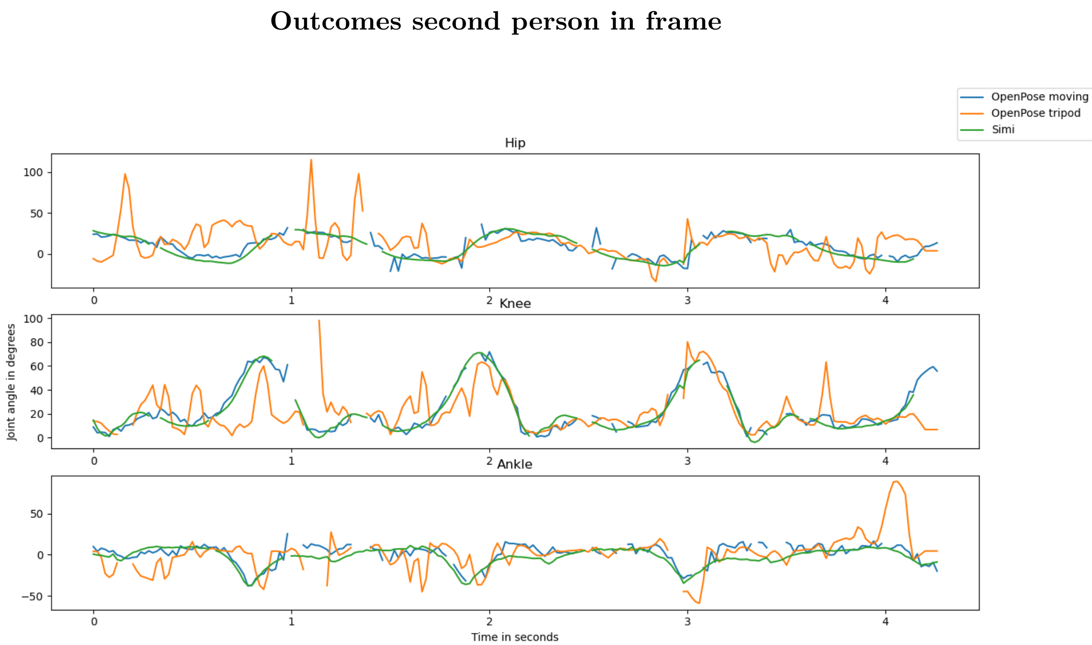

Figure 19: Influence on the joint angels when a second person walks with the person of interest, showing the unfiltered data.

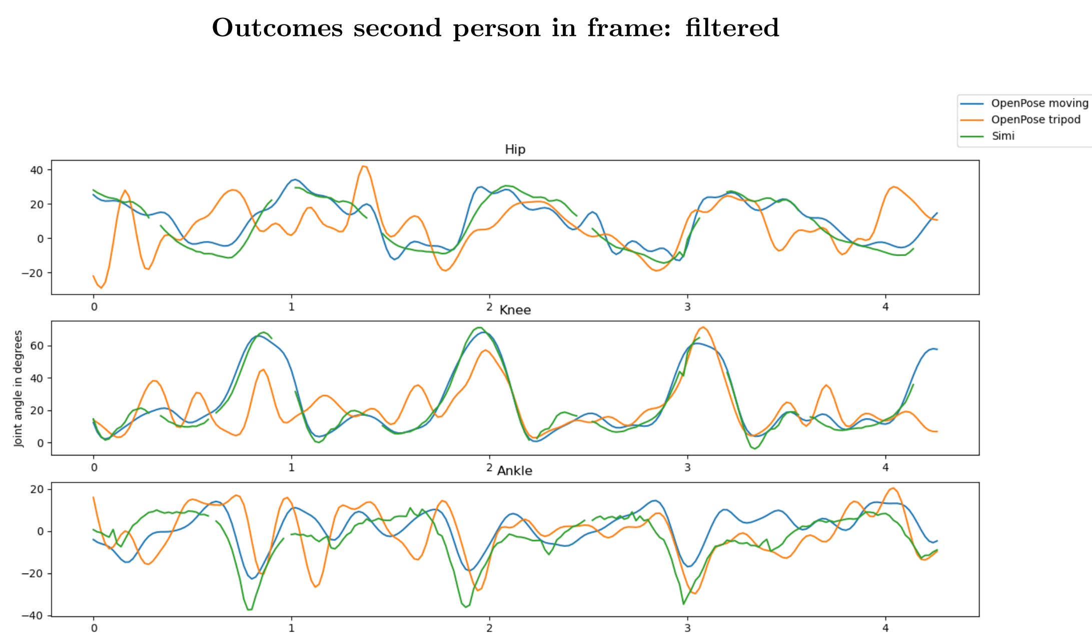

Figure 20: Filtered outcomes of a second person walking with the person of interest.

6.2 Additional: Testing spatiotemporal parameters

The first tests are performed with 4 subjects (N=4) at Basalt The Hague (phase 1). All subjects were women < 30 years old. The subjects all satisfy the criteria as defined in Table 3, with one exception. One subject has a possible deviation in the left hip. However, since it was unsure if the deviation would be visible, and therefore would not have a significant influence on the data processing, the subject is not excluded. During data processing, disturbances in the joint coordinates during gait were found for 3 out of 4 test subjects. Reviewing the recordings, showed the difference of having a second person standing in the background of the frame in the 3 recordings with disturbances. Plotting the joint coordinates of the test subject together with the ones of the background person, showed that the coordinates alternate between the two people. In this case the background person was standing still in the corner of the frame, which made it easy to distinguish the data points from the ones of the test subject, and thus to exchange the data points to the correct person. The spatiotemporal outcomes of all 4 healthy subjects can be found in Table 7.

Outcomes healthy subjects (N=4)

Parameter	**Subject 1****	**Subject 2****	**Subject 3****	**Subject 4**	**Normal value**[44]
Stride right (m)	1.06, 0.73, 1.09	1.02, 1.18, 0.92	1.04, 1.11, 1.25	1.08, 0.83, 0.99	1.362
Stride left (m)	1.13, 0.83	0.99, 0.99	0.74*	1.08, 1.05, 0.76, 0.46	1.362
Step length (m)	0.40, 0.47, 0.56	0.72, 0.43, 0.49	0.21, 0.53	0.46, 0.495, 0.30, 0.56	0.681
Heel clearance right (m)	0.33, 0.26, 0.28	0.35, 0.33, 0.31	0.24, 0.37, 0.22	0.21, 0.23, 0.22	-
Heel clearance left (m)	0.30, 0.34	0.13, 0.18, 0.38, 0.24	0.36, 0.40	0.20, 0.20, 0.21	-
Toe clearance right (m)	0.37, 0.27	0.13, 0.34, 0.39	0.37, 0.35, 0.30	0.11, 0.11, 0.12	-
Toe clearance left (m)	0.23, 0.25, 0.11	0.06, 0.33, 0.12	0.25, 0.22, 0.19, 0.06	0.10, 0.09, 0.10	-
Recording time (s)	3.33	3.50	3.63	3.77	-
Walking speed (m/s)	1.50	1.43	1.38	1.33	1.34

Table 7: Outcomes of spatiotemporal parameters of the 4 healthy test subjects. The normal values are based on an average of results of research testing young adults (≤ 30), similar to the test group characteristics.
$*$ not all steps detected, $**$ corrected for influence of background person in same frame

7 Discussion

7.1 OpenPose verification

In order to reflect on the outcomes generated with the coordinates of OpenPose, the outcomes are compared with the system that is currently used within Basalt: the Simi motion capture system at Basalt Delft. The system is not a golden standard of gait analysis. However since the outcomes of this system are used within the clinical setting and are found to be useful in objectification of gait analysis, these outcomes are used as comparison for verification of the accuracy of OpenPose. Because of the costs, space and mobility of a gait analysis set-up it has been chosen to use a stationary camera on a tripod. In order to see if possible deviations in outcomes between OpenPose and Simi motion capture are not caused by the camera set-up and only by the OpenPose algorithm, OpenPose is also tested on the recordings of the moving camera used at Basalt Delft. Looking at the unfiltered outcomes in Table 4, a decision has been made on which coordinate combinations and which corrections are needed for which joints. The P-values of the correlation coefficients comparing the OpenPose set-ups with the Simi motion capture set-up are very small and thus that the outcomes are statistically significant. There are a few exceptions which are related to errors and will be discussed later. As mentioned in 5.3.2, a linear offset was found in outcomes of the hip angles measured with OpenPose with a stationary camera. In Table 4 it can be concluded that linear correction improves the determination of the hip angles, since the correlation coefficients are, with a few exceptions which will be discussed later, ± 0.90 or higher. The linear offset of the hip can not be explained by distortion of the wide-lens, since this would cause a parabolic offset. A probable explanation of the linear offset could be direction of view on the hip joint. First you look on a relatively front view of the hip, changing towards more sagittal while the person is coming perpendicular to the camera view, and finally moves towards a relatively back view of the hip. Comparing the OpenPose outcomes of the stationary recording and the moving recording, the moving recording has similar or higher correlation coefficients than the stationary recordings. Looking at the knee angles, the correlations are higher with the moving camera (higher than 0.90, but often even ±0.99), but also the stationary camera mostly shows correlations of 0.90 or higher. With regard to the ankle, four ways of determining the joint angles are tested:

(1) coordinates of the ankle and big toe with a 10°offset.
(2) x-ankle with y-heel and big toe.
(3) x-ankle with y-heel and big toe with linear correction similar to the hip.
(4) x-ankle with y-heel and small toe.

Looking at the moving recordings, the highest correlations (±0.70) are found with the x-ankle with y-heel and big toe combination. The stationary recordings also have the highest correlation with this combination of coordinates, but need a linear correction probably because of the same reason as the correction done on the hip angles.

Since the data contains noise, a 6Hz low-pass filter has been applied. The correlation coefficient of the filtered data can be seen in Table 5. Filtering the data leads to higher correlation coefficients. The hip angles measured with OpenPose show a correlation above 0.90 and often even above 0.95, for both the moving recordings and stationary recordings. For the knee similar results are found, both recordings have a correlation above 0.90, where the moving recording gives a better correlation around 0.99. The correlation coefficients are also improved for the ankle angles, however they remain lower than the hip and knee angles (around 0.70 or 0.80). With regard to the choice of anatomical landmarks, both the small toe and big toe are analysed (together with the x-ankle with y-heel combination). The moving recordings mostly (7 out of 10 outcomes) have a higher correlation using the small toe as landmark, whereas the stationary recordings mostly (8 out of 10 outcomes) have higher correlations using the big toe. A possible explanation could be the difference in point of view of both recordings. The moving camera is placed lower than the camera on the tripod. Therefore the camera placed on the tripod has a view more on top of the foot than the moving camera. Whereas the moving camera is more close to the height level of the foot and therefore has a side view of the foot. In a side view, the back toe is more hidden behind the small toe, which could possibly make the measurements with the big toe less accurate.

In conclusion, high correlations are found for the hip and knee angles. The correlation of the ankle angles remain a bit lower. Since the marker position are not exactly the same, and the Simi motion capture system also has some known flaws (for example with regard to using markers), it can not be concluded that the ankle angles measured with OpenPose are wrong. The hip and knee correlations are reliable since the markers are placed on conventional anatomical landmarks. The ankle correlation is less reliable since the the markers are placed differently than most common gait analysis systems and therefore the outcomes can be different as well. Comparison with annotated data or clinical validation is needed to provide a conclusion on the accuracy of the ankle angles measured with OpenPose. In Table 6 can be seen that in most cases the standard deviations remain low. This means that there is a deviation between the different recordings which is most of the time lower than 5 degrees difference. Taking into account the fact that a participant is not able to walk exactly the same, these results prove that OpenPose is repeatable. Looking at the spatiotemporal outcomes in Table 7 and comparing them with the normal values found in literature, the outcomes seem promising but need research to improve and verify the outcomes.

In phase 1 of testing, it was already found that when there was a second person standing in the corner of the frame, OpenPose could not distinguish which coordinates belonged to which person, disturbing the angles measurements of the test participant. A theory was that OpenPose could possibly distinguish different people better, when they were closer together within the frame. This was tested in phase 2 by letting someone walk along with the participant, similar to a situation where a person has a higher risk of falling and needs assistance. In Figure 20 can be seen that the angle measurements contain a lot of noise making the normal angle patterns unrecognisable. Thus, OpenPose seems to be unable to distinguish between several people within the frame. However, while reviewing the recordings, there is little (much less than the amount of disturbances seen in the plots) switching of anatomical landmarks seen between the two persons in the recording. So, there is a discrepancy between the recordings with pose detection and the data analysis outcomes. The cause is found in the JSON-files with the coordinates. Within these files, the persons within the frame are split up and labeled with a number, for example *"person id": [1]*. Looking at the JSON files of the recordings with 2 people within the frame, 2 person id's and data sets are given, however both persons are labeled as *"person id": [-1]*. First of all it is unlogical to label a person as -1. Secondly, the 2 people should not be labeled the same. Probably because of this labeling, OpenPose can not distinguish them causing switching coordinates between them. Since the recordings with the OpenPose pose detection seems to be mostly correct in distinguishing the two different people, the problem is within writing the information to JSON files.

7.1.1 Exceptions results

The general outcomes are discussed above, however exceptions to the general correlation outcomes are found and analysed to determine the cause and if the cause can be overcome. The exceptions can be categorised in the 3 types of errors as mentioned in 6.1.1: (1) start/end, (2) around middle, and (3) spikes. Examples of errors at the start and/or end of the measurements can be seen in Figure 21, Figure 22 and Figure 24. The disruptions are probably caused because the coordinates are too close to the side of the frames and the participants are not fully in the frame. This causes squeezing of landmarks detected by OpenPose towards each other and gaps in the recognition of anatomical landmarks, creating false interpretations of the angles. In the case of Figure 24, the figure shows the disruption of all joint angles at the same time point. The disruption is caused by gaps within the detection of the anatomical landmarks by OpenPose. These gaps are surrounded by outliers in the unfiltered data. The more extreme outliers are removed from the data, however outliers within expected range remain. Because of the gaps and surrounding outliers (within normal range) interpolation created the peaks seen in Figure 24. Examples of errors occuring (mostly) around the middle of the measurements can be seen in Figure 21, Figure 22, and Figure 23. These disruptions are caused by confusion of OpenPose between the legs. This means that the legs are (partly) switched or that both legs are projected on the same leg at the same time. Figure 21 has both, switching of the legs and projection of both the right and left leg on the left leg. Figure 22 is only influenced by switching of the legs. And in Figure 23 the legs are not fully switched, but the left knee is connected with the right hip and vice versa. Since the legs are not fully switched, no mirrored movement is detected (since the legs are always in counter phase of gait). Therefore, this partially switching of the legs causes a smaller disruption than a full switch of the legs. Lastly, an example of a spike can be seen in Figure 25 and Figure 26. In both graphs both, the hip and knee contain a spike (or single outlier) at the same time point. This is caused by wrong labeling of the markers by Simi motion capture. In Figure 25 the foot marker is not detected within this frame, which causes a single frame gap at the ankle angle measurements. The femur-, knee- and foot (in line with the ankle) marker are still detected. As can be seen in Figure 13, the markers have different colours, but the femur- and foot marker are both blue. The spike in Figure 25 is caused by switching the femur- and foot marker within this frame. In Figure 26 a similar situation is happening. This time the femur marker is blocked by the participants hand and therefore not detected. The blue foot marker is detected as both, the foot marker and the femur marker, which causes the outlier in hip and knee angles.

Error 1

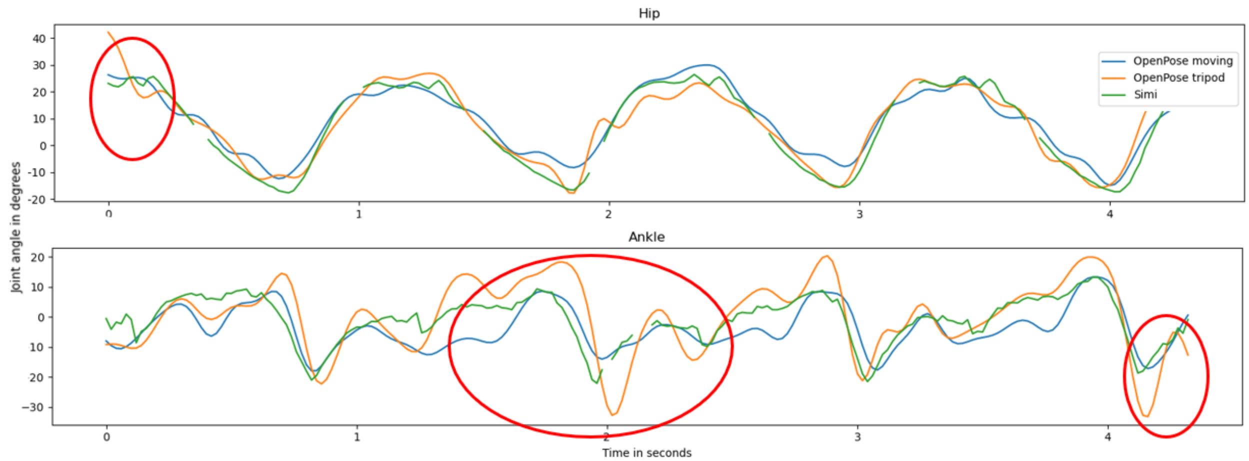

Figure 21: The upper graph shows the hip angles over time. The error in the tripod measurements (orange line) is caused by the fact that the participant is not fully within the frame. In the lower graph the ankle angles can be seen. In the middle the angles are disrupted because OpenPose confuses the left and right leg. The error in the end of the recording is again because the participant is not fully within the frame.

Error 2

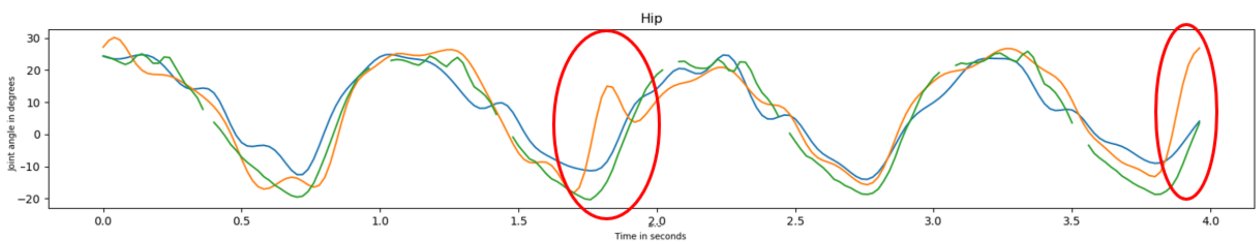

Figure 22: The hip angle graph shows switching of the leg detection in the middle part, and an error in the end because the participant is not fully within the frame.

Error 3

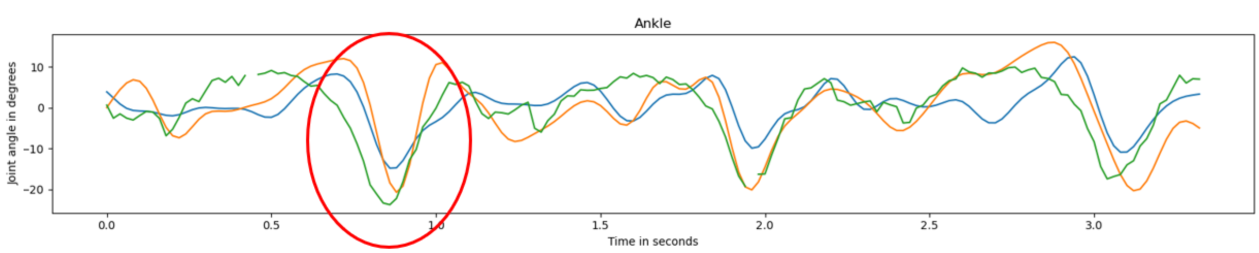

Figure 23: An error can be seen in the tripod measurements (orange line), which is caused by confusion of the legs by OpenPose. In this example the right hip is connected with the leg knee and vice versa.

Error 4

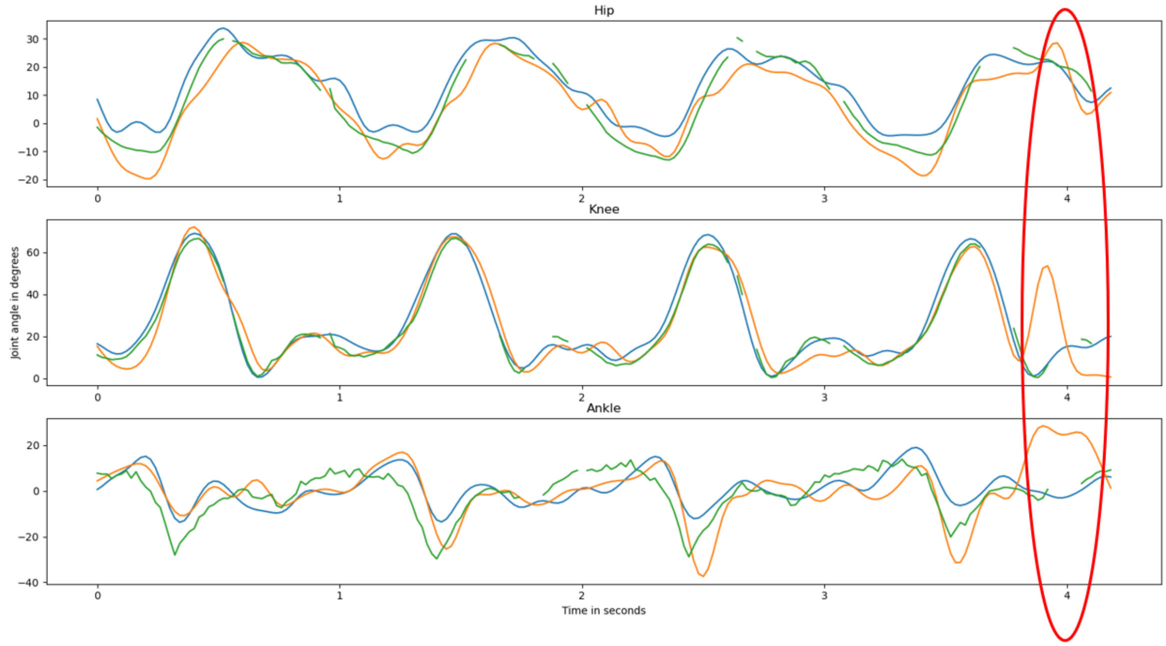

Figure 24: The hip-, knee- and ankle angles of the tripod measurements (orange line) are disrupted at the same moment. This is caused by gaps within the raw data surrounded by outliers (because the participant is not fully within the frame) and interpolation of the gaps for the filtered outcomes, creating false peaks.

Error 5

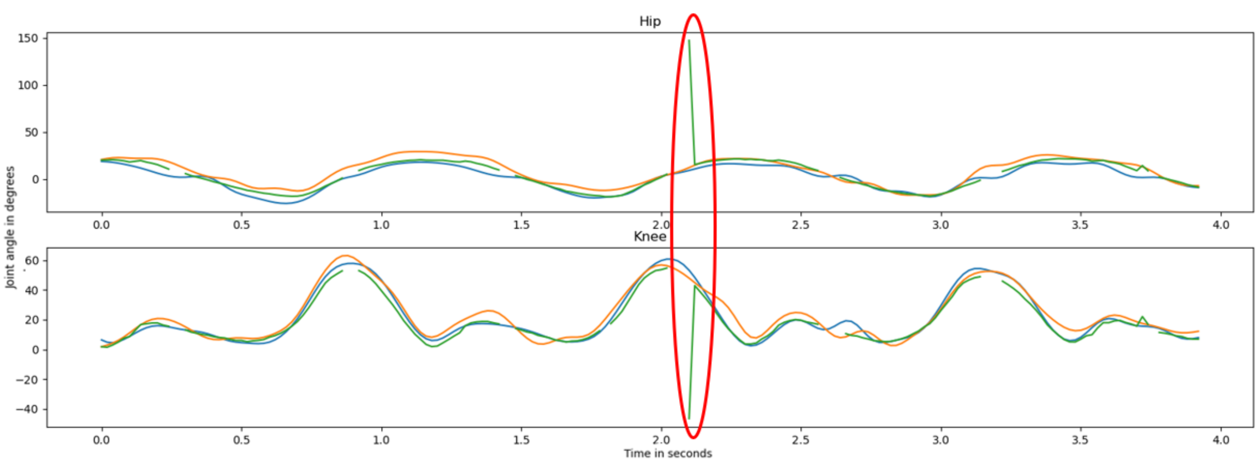

Figure 25: A spike can be seen in the hip- and knee measurements of the Simi motion capture system (green line). The spike is caused by confusion of the femur- and foot marker by the system, which are both blue.

Error 6

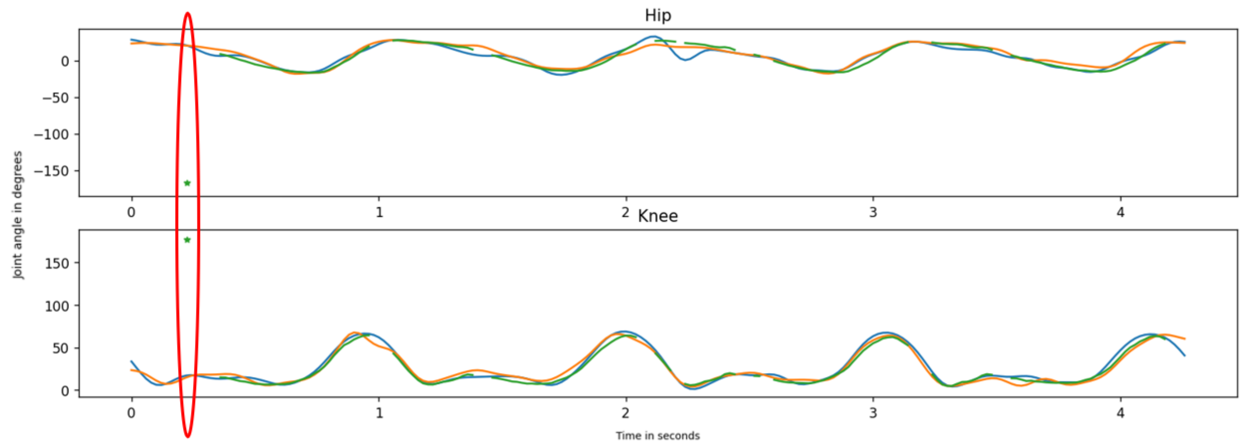

Figure 26: An outlier can be seen in the hip- and knee measurements of the Simi motion capture system (green star). The outlier is caused by detecting the foot marker as both, the femur and foot marker (which are both blue). The real femur marker is blocked by the participants hand and thus not detected.

As mentioned before, in general the standard deviations in Table 6 are low. Higher standard deviations, are due to the same errors as discussed before. Figure 27 consists of more noisy signals in the ankle angles, and Figure 28 shows counter movements in the hip, slightly more variation in the knee angle and noisy ankle angles. All these deviations are caused by confusion of the legs by OpenPose. Notable is that switching of the legs is visible in all three joint angles in all three recordings of participant 4 and therefore have a negative influence on both the correlation coefficients and the standard deviation. Meanwhile, the right recordings of the same participant do not show the same pattern. Possibly this is caused because this participant ended up with the left side at a specific angle, where OpenPose can not distinguish the legs. However, the participant did not end up on the exact same spot every recording, since the gait speed slightly differed between recordings. Therefore, the cause remains unclear.

SD deviations right ankle participant 1

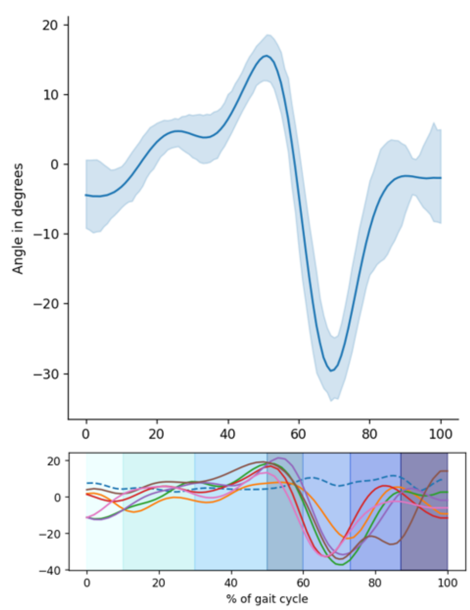

Figure 27: Gait cycle 95% CI plot and standard deviation and error plot per gait cycle for the right ankle of all 3 recordings of participant 1.

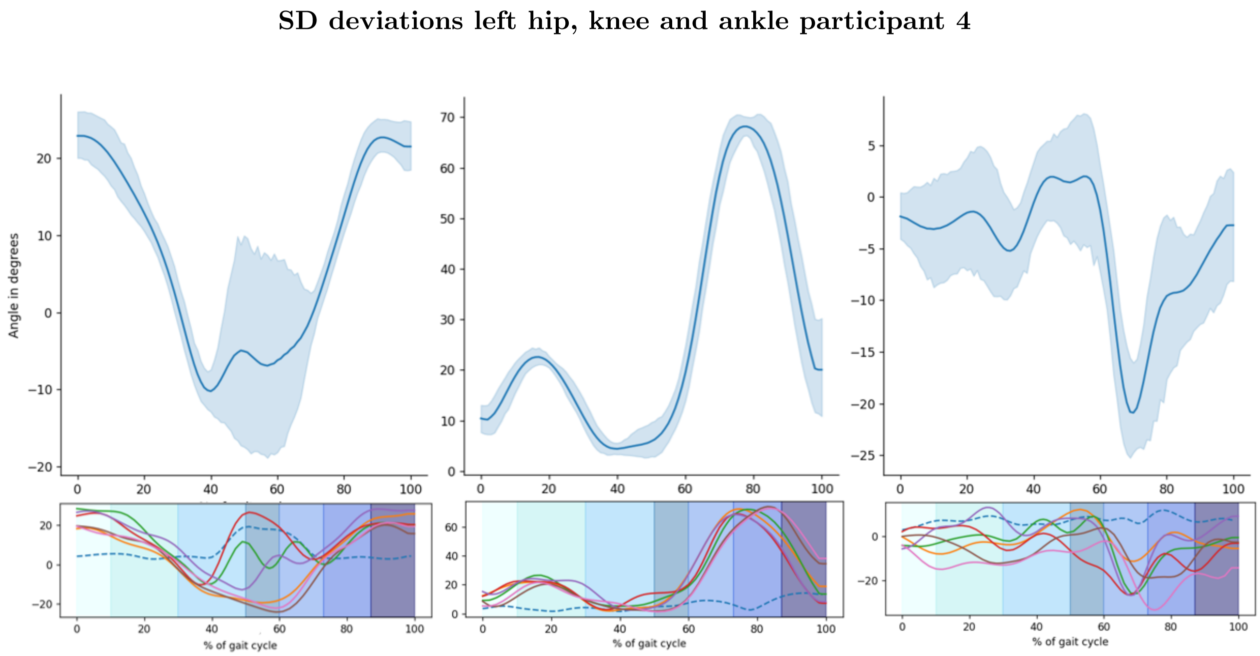

Figure 28: Gait cycle 95% CI plot and standard deviation and error plot per gait cycle for the left hip, knee and ankle of all 3 recordings of participant 4.

7.2 OpenPose feasibility

The feasability of the OpenPose gait analysis set-up is judged on the program of requirements made for implementation of instrumented gait analysis at Basalt rehabilitation clinic at The Hague. The first requirement is the ability to store the data locally. Since no patient data is used within this research, this requirement does not apply yet to the pilot study. With future research and implementation, the videos could be analysed locally and saved in Arqive (central and shielded data storage connected with the electronic patient document (EPD) of Basalt). Another option is to have a local back-up system similar to Basalt Delft. The second requirement is the costs-efficacy. The open-source code is free for use in research (commercial use is $25.000 per year [45]). Data processing with Python is free. Simple smartphone and/or tablet cameras can be used for recording. The third requirement is the space it should fit in at Basalt The Hague. The chosen set-up with tripods and mobile phone cameras is mobile. Currently the room most suitable for this set-up is the physical therapy room showed in Figure 11. The forth requirement is that the system should be generalisable for different types of (abnormal) gait patterns. Within this research the set-up is not clinically validated on different abnormal gait patterns yet. And with current settings it is not possible to use OpenPose for people with a fall-risk, since an assisting person within the frame causes disturbances in the measurements. The fifth requirement, usability, could not be tested in the clinic yet. A graphical user interface (GUI) should be implemented for running OpenPose and for data processing, as well as an output file with all the necessary gait parameters. However, the set-up with tripods and mobile phone cameras is easy to use without extensive training. The sixth requirement is the integration in the clinical process. With the proposed set-up, the same clinical process is performed by the patient Figure 4. The requirement slow-motion rewatch is partly met. Currently recording the patients is not standard procedure. So with implementing instrumented gait analysis, videos are available for rewatching on any moment. Slow-motion is not looked into at the moment, but it should be possible to change the recording speed if wanted. The requirement to be able to compare videos is not looked into during this research. However, it should be possible to subtract data from different recording under different circumstances (e.a. with and without AFO) or at a different time and plot them together to see the differences. Looking at the gait specific requirements, it can be concluded that it is possible to determine joint angles from OpenPose pose-coordinates in the sagittal view. The frontal camera is due to limited time not included within this research. Estimating spatiotemporal parameters with OpenPose pose-coordinates seems promising but needs further improvements and verification.

Feasibility of OpenPose in the clinic

Requirement	OpenPose
Local data storage	✗ Videos can be analysed locally and then saved in Arqive, so it is visible for clinicians in a protected data storage. Another option to have a local back-up system similar to Basalt Delft.
Cost-efficacy	✓ The open-source code is free for use in research. Data processing with Python is free. Simple smartphone and/or tablet cameras can be used for recording.
Space	✓ Suitable for the physical therapy room at Basalt The Hague. Flexible/mobile set-up.
Generalisable	- Not clinically validated on different abnormal gait patterns yet. With current settings not possible to use for people with a fall-risk.
Usability	- GUI for running OpenPose and data processing needs to be implemented, as well as an output file with all the necessary gait parameters. Set-up for recording is simple and does not require extensive training.
Integration	✓ Same clinical process will be performed for the patient.
Slow-motion rewatch	- Slow-motion is currently not implemented. Saving recordings used for gait analysis can also be used for rewatching.
Comparison of videos	✗ Currently not implemented.
Joint angles	✓ Joint angles are calculated by additional data processing of the OpenPose keypoints
Spatiotemporal parameters	- First steps towards estimating spatiotemporal parameters from recordings is done, but further improvement and verification of the outcomes is needed.

Table 8: Feasibility of OpenPose in the clinic tested on the program of requirements.

7.3 Limitations

There are several limitations to this research. First of all, due to limited time choices are made on which elements of the research could be included. For example, a start has been made in estimation of spatiotemporal parameters, however the choice has been made to focus on the kinematic parameters within this research. With regard to the kinematic parameters, more angles can be determined, for example upper body tilt in the sagittal plane and hip tilting in the frontal plane. Due to limited time, also only the sagittal view is used for kinematic outcomes. Also, ideally the kinematic outcomes were clinically validated, which will be discussed in more detail in subsection 7.5.

Secondly, there are limitations with regard to the performed tests in this research. One limitation is the used materials. for the recordings, mobile phones are used that were available for free during the research. Camera's with a higher resolution will probably provide a higher accuracy in pose detection. In Figure 29 the differences in resolution between the mobile phone camera (30fps) and the camera of Basalt Delft (50fps) can be seen. The recordings of the mobile phone camera look blurry and less precise with regard to anatomical landmark detection than the cameras at Basalt Delft. Also the GPU of the available laptop was not sufficient, causing that the resolution had to be decreased to *-1x256* instead of the default *-1x368*. Also, the Simi motion capture system is now used as comparison method for the verification of the OpenPose outcomes. However, this system is no golden standard since it also has its flaws, for example the marker placement and soft-tissue artefacts. During the tests performed at Basalt Delft, issues with the markers are also seen, for example, turning off of the active markers, confusion between markers (as can be seen in Figure 25 and Figure 26), and markers that would not stick on the foot. Another limitation of the performed tests is the variation in participants. The participants were all the same age, but this should not have an influence on the measurements. Also, people with different height and gender are included. Characteristics that are missing amongst the participants that could have an influence on anatomical landmark are more difference in weight and skin colour. Anatomical landmark recognition on people with a higher weight could be more difficult. This also depends on the variety of participants used for training of OpenPose. The same applies to different skin colours. All participants used within this research are white. It depends again on the training data set how accurate pose detection is with a dark skin colour.

Lastly, the chosen test set-up has some limitations. First of all, the patient category that this set-up could be used for at the moment is limited due to the errors in distinguishing multiple people within the frame. Currently it would not be possible to have a second person in the frame and thus it would not be possible to walk along and/or assist a patient with a fall risk. The translation of the OpenPose pose detection to the JSON files needs to be improved with correct labelling of different persons. Another limitation is that the set-up only provides 2D analysis. 3D analysis would provide joint rotations next to the joint angles. It is possible to calibrate multiple cameras and make a 3D analysis of the gait pattern, however this makes the set-up more complex, decreasing the usability, and calibration will increase the needed time, which influences the integration in the clinical processes. Thus, it has an negative influence on the feasibility. Furthermore, from input of therapists and clinicians it remains unclear if there would be a need for 3D analysis of gait and if it would add to the clinical relevance. The system at Basalt Delft is also 2D, so as first step a 2D system would be sufficient and the added value of 3D analysis to the clinical practice can be evaluated.

Camera resolution differences

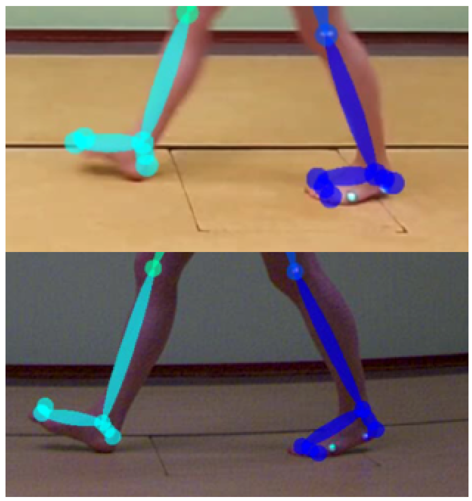

Figure 29: The upper image shows a screenshot of recordings made with the Samsung Galaxy A20e wide view camera, and the lower image of recordings made with the cameras at Basalt Delft.

7.4 Ethics

This research uses healthy participants for testing. All participants are adults and are verbally and written informed about the research and the processing of the recordings and joint coordinates. All participants signed a informed consent, confirming that they apply with the criteria for test participants (see Table 3) and that they give consent for use of their recordings and joint coordinates for this and follow-up research by TU Delft and/or Basalt. All gait outcomes are published anonymous and no images or recordings of the participants are published (except the recordings of the researcher to be able to show the results of the recordings). The tests are performed in underwear or shorts, because of the marker placement. Participants are informed of this before attending the tests, since someone could feel uncomfortable with such recordings. The participants are asked to walk as they would normally do, so no intervention takes place.

Implementation of the set-up proposed in this research in a clinical setting would not disturb the current clinical process. The patient would do the exact same thing as with observational gait analysis. The only addition is that the patient will be recorded. Unlike the tests at Basalt Delft, patients can wear clothes, since the choice to do the tests in underwear or shorts was based on the marker placement. OpenPose is able to perform pose detection with clothes on. Probably it is better to instruct the patients to either come in shorts or tight clothes, so the silhouette remains as much undisturbed as possible. It is preferred to let the patients perform the gait test in clothes instead of underwear to make them feel comfortable. Especially since recordings are involved in the gait analysis. The recordings should also be handled carefully, therefore the data should be either stored on a local back-up system as in Basalt Delft or on Arqive which is already used for sensitive images.

7.5 Recommendations

This research is a pilot study which can be used as a starting point for follow-up research and for future considerations with regard to implementation of instrumented gait analysis at Basalt The Hague. Regarding follow-up research the first recommendation is to see if the errors as discussed before can be prevented or resolved. The errors at the start and end of the recordings can be prevented by only analysing frames where the person is fully within the frame. The switching legs error is not as easy to prevent or resolve. It is possible that this is a current limitation of the AI, but the precise cause remains unknown. The possibility of detecting and maybe even resolving the leg switching could be looked into in more detail in further research. Besides outcomes presented in this research, the following components can be added: upper body tilt (sagittal and frontal view), hip tilting (frontal view), slow-motion and the ability to compare the results with previous results. For determination of upper body tilting, a mid-line keypoint can be defined in a vertical line up from the mid-hip keypoint. The upper body tilt could then be defined as the angle between the midline-midhip vector and the midhip-neck vector. Furthermore, the spatiotemporal parameters need further testing, improvement and verification. Spatiotemporal parameters are an important addition to the gait analysis, since this is a request from the therapists and because this is difficult to determine by observation but tells a lot about the gait pattern. All these recommended additional outcomes and the kinematic outcomes presented in this research need clinical validation. A possible option to perform the clinical validation is to compare observational outcomes and following clinical decisions with the clinical decisions they would make when given the outcomes of instrumented gait analysis. Also the added value of tracking the treatment progress with frequent instrumented gait analysis, and the change in treatment because of this, should be evaluated in a later stage.

With regard to implementation of instrumented gait analysis at Basalt The Hague, with a set-up as proposed (or similar to) in this research the following points are proposed. Instrumented gait analysis at Basalt The Hague, and later on possibly more rehabilitation clinics without a gait analysis lab, should be used as an addition to observational gait analysis and not as an replacement. The low-cost, high usability aspects of this kind of set up should be used for supporting and objectifying observational gait analysis. Also, it is not meant to replace gait analysis as it is done at Basalt Delft. The proposed set-up at Basalt The Hague could be used for frequent analysis to track (the lack of) treatment progress and to serve as a triage tool if a patient should be send to Basalt Delft for a specific problem. In Delft the patient can then be tested with the gait analysis system in combination with physical examinations, EMG and GRF. So the gait analysis in Delft is more extensive and more detailed. When implementing the proposed set-up, a GUI in the form of an app or computer program should be able to enter patient data (e.a. patient number), to add a recording (or even record within this app), to run OpenPose on the recording, to save save the coordinates and to run the data processing steps. Afterwards the recordings need to be available and the coordinates for possible reuse when comparing different results, and a clinical report with gait cycles plots formed by a mean and confidence interval and spatiotemporal outcomes should be given and saved in the EPD. Possibly, with further development deviations can be linked to phases of gait and thus provide an overview of the problem areas in the gait pattern.

Within this research the proposed set-up is with mobile phone cameras on tripods. This decision is made based on the program of requirements and availability of materials. However, OpenPose is also tested on the recordings made with moving camera system at Basalt Delft. The correlation coefficients are mostly higher with the moving camera than the tripod set-up. This can be because of two reasons: the better quality of the camera recordings or the fact that it moves along with the participant. Hence, it could be considered to invest in better quality cameras or a moving camera set-up if the budget allows it. However, the difference in final correlation coefficient between the moving camera and the stationary camera is small. Therefore a more expensive set-up with expensive cameras and possibly a moving camera set-up might be unnecessary. In follow-up research it is recommended to look into the influence of camera quality on OpenPose pose detection.

8 Conclusion

With this research is verified that OpenPose is repeatable and that kinematic parameters of the hip and knee are highly correlated to the standard method of instrumented gait analysis used at Basalt. Therefore can be concluded that OpenPose pose detection seems a promising method for determining kinematic and possibly also spatiotemporal parameters of gait. With follow-up research with especially clinical validation and further development of the data processing, the first steps can be made towards implementation of accessible instrumented gait analysis in the current care path at Basalt Rehabilitation clinic The Hague, and possibly other locations and/or institutions.

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Appendices

Camera specifications

Specifications rear cameras

Samsung Galaxy A20e	
Resolution	13 megapixels (standard camera), 5 megapixels (wide view camera)
F-number	F1.9
FOV	76°(standard camera), 123°(wide view camera)
Video recording resolution	FHD (1920 x 1080 pixels) 30fps
Samsung Galaxy S8	
Resolution	12 megapixels
F-number	F1.7
FOV	88°
Video recording resolution	UHD 4K (3840 x 2160) 30fps

Kinematics comparison

See tables next page.

Correlation Simi motion capture and OpenPose

Participant	**Side**	**Rec**	**Joint angle** correlation (p-value)	**Simi vs moving** correlation (p-value)	**Simi vs tripod** correlation (p-value)	**Moving vs tripod**
1	Left	1	Hip	0.97 (8.06e-119)	0.80 (4.87e-45)	0.78 (4.24e-45)
			Hip*		0.89 (1.72e-68)	0.86 (2.17e-63)
			Knee	0.99 (1.27e-155)	0.96 (1.16e-107)	0.95 (4.50e-103)
			Ankle	0.68 (8.68e-31)	0.67 (1.53e-28)	0.64 (1.35e-25)
			Ankle**	0.78 (1.95e-45)	0.75 (1.29e-38)	0.62 (1.21e-23)
			Ankle***		0.75 (1.17e-38)	0.62 (9.72e-24)
			Ankle****	0.72 (1.15e-35)	0.44 (5.32e-11)	0.31 (4.53e-06)
		3	Hip	0.98 (4.67e-118)	0.84 (4.36e-49)	0.83 (2.99e-49)
			Hip*		0.95 (6.53e-88)	0.93 (1.73e-79)
			Knee	0.99 (8.93e-138)	0.95 (1.32e-89)	0.94 (1.51e-90)
			Ankle	x	x	x
			Ankle**	x	x	x
			Ankle***	x	x	x
			Ankle****	x	x	x
		7	Hip	0.95 (2.53e-101)	0.78 (4.70e-40)	0.79 (2.57e-44)
			Hip*		0.84 (5.06e-50)	0.81 (1.70e-47)
			Knee	0.98 (1.02e-141)	0.98 (1.19e-121)	0.96 (4.07e-114)
			Ankle	0.79 (3.80e-44)	0.68 (2.96e-27)	0.65 (6.18e-25)
			Ankle**	0.87 (2.95e-62)	0.81 (7.18e-47)	0.77 (2.27e-40)
			Ankle***		0.81 (4.73e-47)	0.77 (3.21e-40)
			Ankle****	0.82 (1.80e-49)	0.59 (7.94e-20)	0.56 (2.39e-17)
		2	Hip	0.96 (9.15e-98)	0.88 (1.26e-59)	0.82 (5.76e-49)
			Hip*		0.96 (8.18e-106)	0.94 (2.28e-92)
			Knee	0.98 (8.20e-135)	0.88 (1.18e-58)	0.88 (1.58e-63)
			Ankle	0.65 (2.69e-24)	0.61 (1.96e-20)	0.30 (1.99e-05)
			Ankle**	0.76 (1.91e-36)	0.74 (3.76e-34)	0.64 (2.90e-23)
			Ankle***		0.77 (3.48e-38)	0.66 (4.28e-25)
			Ankle****	0.70 (1.52e-29)	0.76 (3.42e-36)	0.61 (7.63e-21)
		4	Hip	0.97 (1.28e-102)	0.90 (4.92e-63)	0.87 (4.75e-59)
			Hip*		0.97 (7.11e-108)	0.94 (4.02e-87)
			Knee	0.98 (3.21e-130)	0.98 (7.24e-120)	0.96 (6.56e-104)
			Ankle	0.67 (1.78e-25)	0.73 (5.07e-32)	0.40 (1.44e-08)
			Ankle**	0.72 (5.25e-30)	0.79 (2.06e-40)	0.67 (1.01e-25)
			Ankle***		0.80 (6.45e-42)	0.68 (8.81e-27)
			Ankle****	0.68 (6.28e-26)	0.84 (2.56e-50)	0.71 (6.70e-30)
		8	Hip	0.97 (1.21e-94)	0.87 (1.66e-49)	0.87 (3.50e-52)
			Hip*		0.96 (8.90e-86)	0.94 (2.20e-81)
			Knee	0.99 (9.67e-126)	0.96 (4.18e-82)	0.94 (2.30e-78)
			Ankle	0.78 (2.61e-35)	0.61 (4.19e-18)	0.48 (2.68e-11)
			Ankle**	0.84 (5.51e-45)	0.65 (1.08e-21)	0.64 (8.05e-21)
			Ankle***		0.73 (7.66e-29)	0.70 (1.31e-26)
			Ankle****	0.79 (7.25e-37)	0.66 (5.57e-22)	0.74 (3.55e-31)
2	left	1	Hip	0.97 (3.46e-121)	0.87 (1.95e-59)	0.85 (9.17e-54)
			Hip*		0.96 (6.17e-105)	0.93 (3.10e-82)
			Knee	0.99 (1.20e-154)	0.98 (1.63e-123)	0.97 (7.62e-122)
			Ankle	0.61 (8.67e-21)	0.56 (4.16e-17)	0.77 (8.98e-39)
			Ankle**	0.80 (7.25e-43)	0.76 (4.82e-36)	0.80 (9.27e-43)
			Ankle***		0.75 (1.07e-35)	0.80 (4.77e-43)
			Ankle****	0.78 (1.98e-40)	0.26 (3.95e-04)	0.32 (7.10e-06)

Partcipant	Side	Rec	Joint angle correlation (p-value)	Simi vs moving correlation (p-value)	Simi vs tripod correlation (p-value)	Moving vs tripod
		3	Hip	0.95 (5.63e-96)	0.71 (2.21e-28)	0.71 (5.56e-33)
			Hip*		0.74 (1.29e-32)	0.72 (1.51e-34)
			Knee	0.99 (2.20e-136)	0.70 (2.41e-26)	0.71 (1.91e-32)
			Ankle	0.58 (1.88e-19)	0.20 (5.18e-03)	0.43 (6.96e-11)
			Ankle**	0.84 (4.04e-54)	0.56 (1.73e-17)	0.59 (1.19e-19)
			Ankle***		0.55 (2.17e-16)	0.59 (2.53e-20)
			Ankle****	0.81 (3.54e-49)	0.33 (1.93e-06)	0.40 (4.74e-09)
		5	Hip	0.94 (4.58e-84)	0.80 (7.94e-39)	0.78 (6.40e-42)
			Hip*		0.93 (2.01e-76)	0.91 (1.02e-76)
			Knee	0.98 (1.54e-123)	0.96 (1.20e-95)	0.95 (1.67e-101)
			Ankle	0.69 (4.14e-29)	0.30 (1.59e-05)	0.40 (2.75e-09)
			Ankle**	0.82 (2.63e-49)	0.40 (5.54e-09)	0.39 (1.38e-08)
			Ankle***		0.40 (6.11e-09)	0.39 (1.38e-08)
			Ankle****	0.78 (9.53e-43)	0.37 (9.50e-08)	0.34 (8.61e-07)
	right	2	Hip	0.94 (5.63e-90)	0.83 (5.78e-48)	0.71 (8.30e-33)
			Hip*		0.95 (3.12e-92)	0.89 (2.01e-71)
			Knee	0.97 (5.05e-123)	0.98 (3.92e-125)	0.96 (7.14e-112)
			Ankle	0.65 (2.52e-25)	0.46 (5.62e-12)	0.47 (6.78e-13)
			Ankle**	0.71 (7.96e-32)	0.65 (1.73e-25)	0.64 (1.10e-24)
			Ankle***		0.72 (2.71e-33)	0.67 (1.48e-28)
			Ankle****	0.58 (9.80e-20)	0.52 (2.99e-15)	0.61 (4.85e-22)
		4	Hip	0.96 (2.80e-110)	0.86 (5.86e-57)	0.87 (7.17e-68)
			Hip*		0.94 (7.17e-93)	0.91 (9.61e-84)
			Knee	0.98 (1.22e-143)	0.97 (1.50e-121)	0.97 (1.08e-129)
			Ankle	0.59 (2.07e-21)	0.52 (4.82e-16)	0.49 (1.62e-14)
			Ankle**	0.67 (6.55e-29)	0.71 (2.74e-33)	0.55 (1.04e-18)
			Ankle***		0.71 (1.43e-33)	0.56 (3.58e-19)
			Ankle****	0.55 (4.23e-18)	0.63 (7.49e-25)	0.55 (2.22e-17)
		6	Hip	0.96 (6.67e-110)	0.85 (1.41e-55)	0.82 (9.50e-54)
			Hip*		0.95 (3.37e-105)	0.92 (4.94e-88)
			Knee	0.98 (4.05e-134)	0.97 (1.13e-122)	0.96 (6.62e-124)
			Ankle	0.39 (1.06e-08)	0.40 (5.25e-09)	0.34 (3.04e-07)
			Ankle**	0.56 (2.25e-18)	0.64 (7.25e-25)	0.50 (6.51e-15)
			Ankle***		0.68 (6.24e-29)	0.54 (2.12e-17)
			Ankle****	0.50 (2.80e-14)	0.48 (5.91e-13)	0.50 (6.84e-15)
3	left	1	Hip	0.97 (1.26e-109)	0.82 (2.52e-43)	0.80 (1.79e-43)
			Hip*		0.91 (6.90e-70)	0.89 (1.55e-66)
			Knee	0.99 (2.35e-138)	0.98 (1.93e-115)	0.97 (1.33e-123)
			Ankle	0.63 (2.75e-22)	0.26 (4.35e-04)	0.47 (5.25e-12)
			Ankle**	0.78 (1.24e-39)	0.72 (2.22e-31)	0.58 (1.75e-18)
			Ankle***		0.72 (9.10e-31)	0.57 (4.07e-18)
			Ankle****	0.75 (2.17e-35)	0.71 (1.78e-29)	0.54 (4.92e-16)
		3	Hip	0.96 (1.27e-98)	0.86 (1.38e-50)	0.79 (1.11e-40)
			Hip*		0.95 (3.59e-86)	0.89 (2.06e-63)
			Knee	0.98 (3.76e-124)	0.96 (1.41e-94)	0.91 (5.17e-71)
			Ankle	0.64 (1.96e-22)	0.31 (1.62e-05)	0.56 (6.63e-17)
			Ankle**	0.79 (8.32e-40)	0.67 (4.95e-25)	0.63 (2.26e-22)
			Ankle***		0.70 (8.74e-29)	0.67 (1.31e-25)
			Ankle****	0.76 (1.90e-36)	0.47 (1.55e-11)	0.38 (6.15e-08)

Participant	**Side**	**Rec**	**Joint angle** correlation (p-value)	**Simi vs moving** correlation (p-value)	**Simi vs tripod** correlation (p-value)	**Moving vs tripod**
		5	Hip	0.96 (2.72e-92)	0.86 (1.11e-48)	0.85 (1.42e-50)
			Hip*		0.95 (3.04e-81)	0.92 (1.48e-71)
			Knee	0.99 (9.88e-122)	0.97 (2.62e-99)	0.95 (5.57e-94)
			Ankle	0.67 (3.31e-23)	0.35 (2.25e-06)	0.51 (3.91e-13)
			Ankle**	0.80 (1.13e-38)	0.64 (1.15e-20)	0.59 (7.76e-18)
			Ankle***		0.65 (1.70e-21)	0.62 (5.04e-20)
			Ankle****	0.76 (7.43e-33)	0.39 (1.54e-07)	0.22 (2.65e-03)
	right	2	Hip	0.96 (1.36e-83)	0.86 (9.31e-46)	0.81 (1.05e-39)
			Hip*		0.95 (3.29e-75)	0.91 (4.91e-63)
			Knee	0.99 (4.36e-121)	0.97 (9.57e-90)	0.95 (9.85e-86)
			Ankle	0.51 (4.31e-12)	0.29 (1.69e-04)	0.38 (5.82e-07)
			Ankle**	0.69 (1.86e-24)	0.64 (1.01e-19)	0.57 (1.05e-15)
			Ankle***		0.63 (1.66e-19)	0.58 (2.96e-16)
			Ankle****	0.68 (9.35e-24)	0.66 (1.18e-21)	0.67 (2.35e-22)
		4	Hip	0.79 (1.96e-39)	0.66 (1.85e-24)	0.75 (6.79e-37)
			Hip*		0.78 (5.07e-39)	0.91 (8.75e-78)
			Knee	0.87 (1.96e-55)	0.74 (4.36e-32)	0.83 (3.07e-51)
			Ankle	0.49 (4.78e-13)	0.51 (1.04e-13)	0.42 (1.54e-09)
			Ankle**	0.68 (3.70e-27)	0.75 (1.24e-34)	0.65 (4.28e-25)
			Ankle***		0.78 (3.49e-39)	0.68 (6.62e-28)
			Ankle****	0.63 (3.24e-22)	0.71 (2.43e-30)	0.64 (3.54e-24)
		6	Hip	0.96 (2.08e-108)	0.84 (1.23e-48)	0.80 (8.56e-44)
			Hip*		0.96 (1.11e-104)	0.92 (2.08e-81)
			Knee	0.98 (1.25e-131)	0.97 (7.54e-107)	0.95 (9.91e-102)
			Ankle	0.51 (5.58e-14)	0.44 (2.16e-10)	0.41 (2.03e-09)
			Ankle**	0.71 (6.99e-31)	0.69 (1.51e-28)	0.65 (3.84e-24)
			Ankle***		0.73 (3.85e-33)	0.68 (1.69e-27)
			Ankle****	0.68 (3.16e-27)	0.72 (7.50e-32)	0.74 (7.41e-35)
4	left	1	Hip	0.98 (1.77e-111)	0.89 (8.69e-53)	0.88 (4.58e-53)
			Hip*		0.90 (4.52e-55)	0.88 (1.48e-53)
			Knee	0.99 (3.51e-143)	0.99 (9.71e-115)	0.98 (5.54e-106)
			Ankle	0.48 (2.14e-10)	0.23 (3.96e-03)	0.49 (8.61e-11)
			Ankle**	0.69 (8.47e-24)	0.57 (1.68e-14)	0.67 (6.74e-22)
			Ankle***		0.58 (2.32e-15)	0.66 (6.41e-21)
			Ankle****	0.61 (1.68e-17)	0.58 (1.87e-15)	0.41 (8.24e-08)
		3	Hip	0.97 (4.24e-99)	0.67 (4.19e-23)	0.66 (8.74e-23)
			Hip*		0.71 (3.99e-26)	0.69 (1.97e-25)
			Knee	0.99 (1.11e-135)	0.88 (8.51e-53)	0.87 (7.88e-53)
			Ankle	0.46 (4.41e-10)	0.07 (0.36)	0.25 (1.32e-03)
			Ankle**	0.69 (2.15e-25)	0.25 (1.37e-03)	0.34 (7.99e-06)
			Ankle***		0.27 (4.78e-04)	0.36 (2.56e-06)
			Ankle****	0.69 (1.28e-24)	0.25 (1.29e-03)	0.31 (7.15e-05)
		5	Hip	0.96 (5.10e-103)	0.64 (2.09e-21)	0.61 (9.05e-20)
			Hip*		0.72 (4.23e-29)	0.71 (3.24e-29)
			Knee	0.99 (1.072e-148)	0.98 (3.46e-115)	0.96 (1.68e-106)
			Ankle	0.56 (6.30e-17)	0.01 (0.92)	0.18 (1.75e-02)
			Ankle**	0.75 (4.16e-34)	0.21 (5.03e-03)	0.29 (9.91e-05)
			Ankle***		0.22 (2.82e-03)	0.31 (1.91e-05)
			Ankle****	0.71 (9.09e-30)	0.17 (2.30e-02)	0.21 (4.14e-03)

Participant	**Side**	**Rec**	**Joint angle** correlation (p-value)	**Simi vs moving** correlation (p-value)	**Simi vs tripod** correlation (p-value)	**Moving vs tripod**
	right	2	Hip	0.97 (7.25e-88)	0.87 (7.29e-44)	0.89 (1.90e-62)
			Hip*		0.92 (7.68e-58)	0.90 (3.22e-65)
			Knee	0.99 (1.76e-124)	0.92 (4.79e-57)	0.92 (7.17e-74)
			Ankle	0.75 (8.91e-33)	0.38 (2.82e-07)	0.33 (6.67e-06)
			Ankle**	0.81 (1.56e-42)	0.48 (3.75e-11)	0.54 (8.14e-15)
			Ankle***		0.51 (1.02e-12)	0.57 (2.60e-16)
			Ankle****	0.75 (2.23e-33)	0.47 (1.11e-10)	0.55 (2.55e-15)
		4	Hip	0.97 (4.86e-81)	0.82 (2.40e-33)	0.82 (7.98e-42)
			Hip*		0.90 (9.19e-49)	0.88 (3.20e-56)
			Knee	0.99 (3.99e-113)	0.90 (9.97e-47)	0.89 (9.12e-57)
			Ankle	0.80 (1.53e-38)	0.40 (1.58e-07)	0.35 (4.58e-06)
			Ankle**	0.83 (2.49e-43)	0.76 (1.10e-31)	0.69 (4.97e-25)
			Ankle***		0.81 (7.13e-38)	0.74 (1.45e-29)
			Ankle****	0.82 (8.32e-41)	0.80 (1.30e-37)	0.68 (3.83e-24)
		6	Hip	0.97 (3.79e-83)	0.85 (4.23e-38)	0.86 (1.40e-51)
			Hip*		0.91 (5.35e-51)	0.92 (6.82e-70)
			Knee	0.99 (3.90e-121)	0.87 (4.78e-40)	0.87 (2.81e-55)
			Ankle	0.78 (1.02e-36)	0.48 (1.02e-10)	0.21 (6.47e-03)
			Ankle**	0.84 (1.02e-46)	0.78 (1.23e-35)	0.45 (5.46e-10)
			Ankle***		0.79 (1.63e-36)	0.46 (3.09e-10)
			Ankle****	0.77 (3.91e-35)	0.80 (1.04e-37)	0.54 (3.90e-14
5	left	1	Hip	0.98 (8.46e-125)	0.71 (1.24e-29)	0.74 (2.40e-35)
			Hip*		0.73 (1.37e-31)	0.74 (6.53e-35)
			Knee	0.99 (7.64e-146)	0.97 (1.39e-111)	0.96 (6.49e-114)
			Ankle	0.61 (3.09e-21)	0.42 (1.43e-09)	0.56 (6.64e-18)
			Ankle**	0.81 (6.84e-46)	0.62 (3.31e-22)	0.64 (1.04e-23)
			Ankle***		0.65 (3.34e-24)	0.65 (2.39e-25)
			Ankle****	0.80 (2.96e-44)	0.53 (2.24e-15)	0.54 (6.58e-16)
		3	Hip	0.97 (7.02e-118)	0.88 (2.99e-59)	0.87 (1.49e-58)
			Hip*		0.97 (3.84e-105)	0.94 (1.23e-90)
			Knee	0.98 (2.25e-134)	0.96 (1.22e-99)	0.95 (5.24e-98)
			Ankle	0.57 (1.98e-17)	0.19 (8.56e-03)	0.42 (2.42e-09)
			Ankle**	0.73 (2.58e-32)	0.47 (5.91e-12)	0.47 (9.64e-12)
			Ankle***		0.48 (4.51e-12)	0.47 (8.62e-12)
			Ankle****	0.64 (8.60e-23)	0.40 (9.18e-09)	0.41 (6.45e-09)
		5	Hip	0.97 (1.43e-114)	0.84 (6.41e-50)	0.83 (4.26e-52)
			Hip*		0.95 (6.75e-92)	0.93 (6.82e-86)
			Knee	0.99 (8.90e-144)	0.92 (1.15e-79)	0.91 (8.96e-79)
			Ankle	0.60 (6.60e-21)	0.38 (5.60e-08)	0.48 (6.22e-13)
			Ankle**	0.70 (1.49e-30)	0.50 (5.82e-14)	0.53 (6.47e-16)
			Ankle***		0.51 (1.42e-14)	0.54 (1.07e-16)
			Ankle****	0.65 (4.96e-25)	0.42 (1.06e-09)	0.39 (1.37e-08)
	right	2	Hip	0.96 (1.56e-76)	0.81 (6.05e-34)	0.80 (9.05e-43)
			Hip*		0.95 (8.96e-74)	0.93 (2.47e-83)
			Knee	0.99 (1.24e-111)	0.96 (2.62e-81)	0.96 (4.35e-104)
			Ankle	0.70 (3.19e-29)	0.74 (4.12e-33)	0.68 (8.77e-27)
			Ankle**	0.73 (1.13e-32)	0.76 (6.80e-37)	0.72 (5.75e-32)
			Ankle***		0.78 (2.89e-40)	0.74 (1.04e-34)
			Ankle****	0.61 (2.28e-20)	0.69 (7.71e-28)	0.71 (5.43e-30)

Participant	Side	Rec	Joint angle correlation (p-value)	Simi vs moving correlation (p-value)	Simi vs tripod correlation (p-value)	Moving vs tripod
		4	Hip	0.62 (2.30e-19)	0.47 (1.15e-10)	0.76 (8.05e-41)
			Hip*		0.63 (2.81e-20)	0.89 (5.94e-75)
			Knee	0.82 (3.34e-42)	0.80 (2.29e-39)	0.96 (1.06e-115)
			Ankle	0.71 (9.65e-34)	0.76 (7.41e-40)	0.67 (2.40e-29)
			Ankle**	0.73 (8.54e-37)	0.81 (4.86e-49)	0.74 (1.67e-37)
			Ankle***		0.81 (6.95e-50)	0.74 (1.48e-37)
			Ankle****	0.60 (1.31e-21)	0.81 (1.63e-49)	0.72 (1.40e-34)
		6	Hip	0.94 (2.25e-80)	0.78 (3.25e-36)	0.77 (4.62e-43)
			Hip*		0.93 (2.41e-74)	0.90 (6.76e-75)
			Knee	0.98 (6.40e-131)	0.97 (8.93e-102)	0.94 (1.81e-100)
			Ankle	0.72 (4.14e-34)	0.65 (7.25e-26)	0.60 (2.10e-21)
			Ankle**	0.79 (1.52e-45)	0.75 (1.27e-38)	0.74 (2.19e-36)
			Ankle***		0.76 (6.29e-39)	0.74 (2.36e-36)
			Ankle****	0.68 (9.12e-30)	0.68 (1.23e-28)	0.72 (3.09e-34)

Correlation Simi motion capture and OpenPose: Filtered data

Participant	Side	Rec	Joint angle	Simi vs moving correlation (p-value)	Simi vs tripod correlation (p-value)	Moving vs tripod correlation (p-value)
1	Left	1	Hip	0.98 (1.73e-130)	0.95 (3.65e-104)	0.93 (9.71e-96)
			Knee	0.99 (1.86e-175)	0.97 (6.37e-118)	0.96 (1.19e-121)
			Ankle	0.75 (1.07e-39)	0.77 (3.19e-44)	0.75 (5.48e-40)
			Ankle*	0.76 (4.84e-41)	0.63 (2.37e-25)	0.49 (1.52e-14)
	left	3	Hip	0.98 (3.38e-129)	0.96 (3.27e-98)	0.95 (1.79e-95)
			Knee	0.99 (2.10e-155)	0.96 (2.97e-98)	0.96 (4.82e-105)
			Ankle	x	x	x
			Ankle**	x	x	x
		7	Hip	0.97 (1.79e-113)	0.91 (3.37e-71)	0.88 (3.23e-65)
			Knee	0.99 (5.42e-159)	0.98 (8.49e-133)	0.98 (4.28e-135)
			Ankle**	0.85 (6.12e-56)	0.84 (9.58e-55)	0.78 (1.50e-41)
			Ankle****	0.85 (1.71e-55)	0.72 (2.45e-32)	0.73 (4.18e-34)
	right	2	Hip	0.96 (1.75e-104)	0.97 (2.06e-117)	0.96 (1.40e-109)
			Knee	0.99 (2.42e-143)	0.97 (3.08e-105)	0.97 (1.14e-122)
			Ankle	0.68 (6.09e-27)	0.78 (2.47e-40)	0.52 (7.18e-15)
			Ankle**	0.72 (2.78e-31)	0.77 (1.91e-37)	0.72 (1.79e-32)
		4	Hip	0.97 (6.67e-112)	0.98 (2.50e-123)	0.96 (7.17e-105)
			Knee	0.99 (2.73e-146)	0.98 (1.28e-127)	0.97 (5.21e-118)
			Ankle	0.73 (1.81e-31)	0.81 (4.13e-43)	0.62 (6.25e-21)
			Ankle**	0.70 (8.28e-28)	0.85 (3.59e-53)	0.77 (7.49e-37)
		8	Hip	0.98 (4.10e-109)	0.97 (2.51e-96)	0.96 (3.91e-97)
			Knee	0.99 (6.56e-141)	0.96 (3.08e-88)	0.95 (1.79e-89)
			Ankle	0.82 (4.01e-42)	0.77 (1.65e-34)	0.70 (1.50e-26)
			Ankle**	0.82 (3.73e-41)	0.65 (3.04e-21)	0.77 (1.72e-34)

Partcipant	**Side**	**Rec**	**Joint angle**	**Simi vs moving** correlation (p-value)	**Simi vs tripod** correlation (p-value)	**Moving vs tripod** correlation (p-value)
2	left	1	Hip	0.98 (1.56e-140)	0.97 (7.11e-118)	0.95 (5.93e-99)
			Knee	0.99 (1.56e-140)	0.98 (3.58e-135)	0.98 (2.35e-141)
			Ankle	0.66 (6.34e-25)	0.74 (3.12e-34)	0.72 (5.74e-32)
			Ankle**	0.82 (1.34e-47)	0.57 (2.46e-18)	0.68 (1.11e-27)
		3	Hip	0.97 (5.25e-110)	0.94 (8.09e-87)	0.93 (1.08e-94)
			Knee	0.99 (7.82e-146)	0.92 (1.74e-71)	0.90 (2.83e-77)
			Ankle	0.63 (1.34e-23)	0.60 (1.34e-21)	0.56 (2.27e-18)
			Ankle**	0.86 (2.79e-58)	0.62 (1.37e-22)	0.66 (1.46e-27)
		5	Hip	0.95 (2.83e-91)	0.95 (4.78e-87)	0.93 (5.70e-92)
			Knee	0.99 (4.49e-133)	0.97 (1.12e-108)	0.97 (1.33e-120)
			Ankle	0.71 (2.00e-32)	0.76 (1.32e-38)	0.76 (2.53e-39)
			Ankle**	0.82 (1.51e-50)	0.59 (4.33e-20)	0.70 (2.40e-31)
	right	2	Hip	0.95 (1.89e-97)	0.96 (3.37e-103)	0.93 (1.14e-90)
			Knee	0.98 (1.03e-130)	0.98 (7.04e-137)	0.98 (2.78e-139)
			Ankle	0.73 (1.46e-34)	0.74 (6.99e-37)	0.67 (4.14e-29)
			Ankle**	0.64 (1.55e-24)	0.53 (3.45e-16)	0.69 (2.71e-31)
		4	Hip	0.97 (9.18e-120)	0.95 (9.22e-101)	0.93 (1.38e-94)
			Knee	0.99 (4.63e-156)	0.98 (2.89e-129)	0.98 (1.10e-146)
			Ankle	0.67 (1.74e-28)	0.76 (2.07e-40)	0.73 (9.80e-38)
			Ankle**	0.61 (5.61e-23)	0.67 (2.51e-28)	0.65 (5.98e-27)
		6	Hip	0.97 (2.42e-120)	0.97 (2.43e-118)	0.94 (7.65e-102)
			Knee	0.99 (4.24e-147)	0.98 (1.78e-134)	0.98 (8.63e-146)
			Ankle	0.45 (1.47e-11)	0.75 (4.35e-37)	0.46 (7.77e-13)
			Ankle**	0.55 (2.98e-17)	0.52 (2.74e-15)	0.59 (3.39e-21)
3		1	Hip	0.98 (3.82e-126)	0.98 (8.99e-125)	0.96 (6.45e-105)
			Knee	0.99 (1.34e-162)	0.98 (2.95e-120)	0.98 (9.25e-137)
			Ankle	0.71 (5.08e-30)	0.74 (3.36e-34)	0.77 (4.02e-40)
			Ankle**	0.79 (2.18e-42)	0.75 (1.48e-35)	0.61 (1.73e-21)
		3	Hip	0.97 (4.11e-108)	0.96 (3.99e-94)	0.91 (1.09e-73)
			Knee	0.99 (1.29e-139)	0.98 (3.54e-114)	0.97 (1.01e-109)
			Ankle	0.71 (4.05e-29)	0.76 (2.33e-35)	0.78 (6.80e-39)
			Ankle**	0.81 (3.61e-43)	0.61 (8.31e-20)	0.56 (7.96e-17)
		5	Hip	0.97 (5.73e-104)	0.96 (5.24e-92)	0.95 (5.56e-88)
			Knee	0.99 (2.58e-142)	0.99 (1.46e-122)	0.98 (3.16e-117)
			Ankle	0.73 (1.49e-29)	0.69 (2.06e-25)	0.79 (1.86e-38)
			Ankle**	0.80 (4.45e-39)	0.61 (1.94e-18)	0.44 (1.06e-09)
	right	2	Hip	0.97 (6.85e-96)	0.96 (7.71e-83)	0.93 (5.61e-73)
			Knee	0.99 (8.35e-146)	0.97 (6.97e-100)	0.98 (6.78e-110)
			Ankle	0.58 (1.83e-16)	0.67 (1.36e-22)	0.71 (5.03e-27)
			Ankle**	0.75 (4.69e-31)	0.69 (2.65e-24)	0.74 (5.87e-30)
		4	Hip	0.81 (1.77e-42)	0.79 (5.79e-40)	0.93 (1.09e-88)
			Knee	0.87 (1.58e-57)	0.87 (1.60e-57)	0.97 (1.32e-124)
			Ankle	0.57 (3.39e-18)	0.81 (5.37e-46)	0.71 (2.82e-31)
			Ankle**	0.68 (1.00e-27)	0.73 (8.34e-33)	0.72 (1.04e-32)
		6	Hip	0.97 (1.95e-121)	0.97 (1.32e-120)	0.95 (1.13e-97)
			Knee	0.99 (7.58e-146)	0.96 (9.09e-104)	0.95 (3.15e-103)
			Ankle	0.58 (7.47e-19)	0.77 (9.12e-39)	0.53 (1.05e-15)
			Ankle**	0.73 (4.01e-33)	0.74 (4.41e-34)	0.80 (4.76e-45)

Participant	**Side**	**Rec**	**Joint angle**	**Simi vs moving** correlation (p-value)	**Simi vs tripod** correlation (p-value)	**Moving vs tripod** correlation (p-value)
4	left	1	Hip	0.99 (2.01e-125)	0.92 (1.40e-62)	0.91 (1.72e-61)
			Knee	1.00 (6.25e-170)	0.99 (1.29e-120)	0.98 (7.56e-116)
			Ankle	0.54 (3.23e-13)	0.61 (3.86e-17)	0.63 (2.22e-19)
			Ankle**	0.69 (2.08e-23)	0.75 (1.72e-29)	0.63 (3.66e-19)
		3	Hip	0.97 (6.76e-105)	0.88 (4.08e-54)	0.87 (1.22e-52)
			Knee	0.99 (9.43e-151)	0.99 (1.52e-126)	0.98 (4.12e-123)
			Ankle	0.53 (1.23e-13)	0.66 (4.75e-22)	0.63 (1.92e-20)
			Ankle**	0.72 (2.24e-28)	0.56 (1.67e-15)	0.55 (1.81e-14)
		5	Hip	0.97 (1.74e-105)	0.77 (8.63e-37)	0.78 (3.86e-40)
			Knee	0.99 (4.07e-168)	0.98 (4.49e-120)	0.97 (4.89e-113)
			Ankle	0.63 (1.60e-21)	0.32 (6.92e-06)	0.01 (0.93)
			Ankle**	0.74 (1.20e-33)	0.58 (2.86e-18)	0.64 (3.89e-23)
	right	2	Hip	0.98 (6.25e-97)	0.93 (2.90e-61)	0.91 (1.42e-69)
			Knee	1.00 (3.63e-140)	0.99 (7.20e-113)	0.99 (3.57e-146)
			Ankle	0.81 (8.35e-43)	0.87 (5.52e-56)	0.79 (2.89e-40)
			Ankle**	0.78 (6.52e-38)	0.80 (3.32e-41)	0.83 (1.47e-47)
		4	Hip	0.97 (4.06e-88)	0.90 (1.61e-50)	0.90 (5.18e-61)
			Knee	0.99 (5.90e-127)	0.96 (7.09e-74)	0.95 (2.23e-85)
			Ankle	0.85 (6.30e-46)	0.81 (1.65e-39)	0.82 (7.56e-43)
			Ankle**	0.85 (3.13e-47)	0.82 (6.29e-41)	0.79 (6.33e-38)
		6	Hip	0.98 (3.43e-93)	0.90 (1.37e-49)	0.90 (4.71e-66)
			Knee	1.00 (1.46e-136)	0.93 (9.76e-60)	0.94 (5.16e-84)
			Ankle	0.83 (2.84e-45)	0.75 (2.74e-32)	0.74 (1.80e-32)
			Ankle**	0.79 (6.86e-39)	0.75 (3.13e-33)	0.70 (1.23e-27)
5	left	1	Hip	0.98 (1.38e-140)	0.94 (3.66e-90)	0.94 (2.54e-96)
			Knee	0.99 (1.42e-159)	0.97 (3.63e-119)	0.97 (7.03e-128)
			Ankle	0.71 (8.26e-32)	0.67 (1.68e-26)	0.51 (1.04e-14)
			Ankle**	0.84 (1.84e-53)	0.77 (5.29e-39)	0.79 (1.03e-43)
		3	Hip	0.98 (8.70e-132)	0.98 (5.06e-118)	0.96 (2.59e-108)
			Knee	0.99 (7.95e-155)	0.97 (1.02e-111)	0.97 (1.78e-114)
			Ankle	0.63 (1.56e-22)	0.52 (3.84e-14)	0.50 (1.97e-13)
			Ankle**	0.70 (1.33e-28)	0.56 (6.63e-17)	0.62 (1.52e-21)
		5	Hip	0.98 (3.30e-132)	0.96 (3.55e-103)	0.95 (4.17e-101)
			Knee	0.99 (2.17e-162)	0.94 (5.21e-89)	0.93 (9.17e-90)
			Ankle	0.68 (4.26e-28)	0.53 (7.41e-16)	0.52 (1.94e-15)
			Ankle**	0.69 (1.26e-28)	0.58 (1.17e-18)	0.60 (8.63e-21)
		2	Hip	0.97 (5.48e-84)	0.97 (5.85e-85)	0.95 (2.13e-95)
			Knee	0.99 (3.09e-124)	0.97 (2.94e-93)	0.97 (3.85e-121)
			Ankle	0.79 (1.14e-40)	0.82 (7.72e-46)	0.81 (6.23e-46)
			Ankle**	0.68 (2.96e-26)	0.72 (1.18e-30)	0.81 (4.23e-45)
		4	Hip	0.62 (2.36e-19)	0.65 (1.66e-21)	0.94 (2.16e-98)
			Knee	0.82 (1.55e-42)	0.81 (2.69e-40)	0.97 (4.25e-135)
			Ankle	0.79 (6.46e-47)	0.84 (2.53e-56)	0.80 (6.33e-50)
			Ankle**	0.69 (4.99e-31)	0.84 (4.08e-56)	0.83 (1.01e-54)
		6	Hip	0.95 (6.85e-88)	0.95 (3.84e-85)	0.93 (2.37e-92)
			Knee	0.99 (1.88e-144)	0.97 (5.42e-108)	0.97 (1.54e-128)
			Ankle	0.77 (4.43e-42)	0.78 (5.73e-44)	0.76 (4.66e-41)
			Ankle**	0.71 (2.54e-33)	0.69 (2.46e-31)	0.80 (4.64e-48)