



Christian Wresnig, BSc

Quantitative evaluation of an IMU-based gait analysis system: Motionsensor

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Supervisor

Assoc.Prof. Dipl.-Ing. Dr.techn. Reinhold Scherer

Institute of Neural Engineering

Head: Univ.-Prof. Dipl.-Ing. Dr.techn. Gernut Müller-Putz

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Thanks

I would like to thank the company Tyromotion, because I was able to do my thesis there. First and foremost, Alexander, who granted me great freedom during the work. Andreas, who was always available with advice and assistance with his expertise. He also made it possible to use the zebris system for testing. I would also like to thank all other company members at this point.

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My family, because they gave me the freedom I needed to complete my work.

Abstract

This thesis deals with the evaluation and verification of a gait analysis system, based on Inertial Measurement Units (IMU). The measured values are compared with a widely used system (zebris Rehawalk). A framework for data acquisition and evaluation was implemented. Furthermore, the integration of the algorithm for the evaluation of the gait phases and the spatio-temporal parameters is needed. The system is tested with 19 subjects, each had to perform three measurements (three, five and again three $\frac{km}{h}$ with a restriction of the flexion of the right knee), altogether 57 records. The evaluation is done with descriptive and inferential statistics using a significance level of $\alpha = 0.05$. The evaluation shows that the errors are within a four percent range. The highest deviations result in the determination of the distance. The swing and stance phase is determined with less than two percent aberration. The statistical analysis shows that the mean values of both systems are different. Furthermore, there were significant differences between the normal gait with three $\frac{km}{h}$ and the others, with the used $\alpha = 0.05$.

Keywords: gait analysis, inertial measurement unit (IMU), accelerometer, gyroscope, gait phase detection

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Acronyms

DLL Dynamic Link Library

FF Foot-Flat

GUI Graphical User Interface

IDE Integrated Development Environment

IMU Inertial Measurement Units

LR Loading Response

MLD Maximum Lateral Deviation

MSt Mid-Stance

MZP Maximum Z Position

PSw Pre-Swing

RF Restriction of the Flexion of the right knee

ST Stance

SW Swing

TSt Terminal-Stance

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1. Introduction

The man's gait was uneven, like his legs were different lengths. He teetered as he walked, wobbling from side to side, with every step looking as if he were about to stumble. [1]

This verse gives a description of a human gait. Nobody knows anything about the conditions of that person. The reader can only guess; is the man drunken, ill, impaired or disabled. Maybe all of them, maybe nothing or - something else. The gait is a complex sequence of events, an interaction of muscles, bones and joints. Different tasks are supported during the human gait, for example, the forward movement of the body or the weight distribution. To investigate the gait or a gait cycle, specific knowledge about this topic is necessary. An untaught person cannot distinguish between a health and an impaired gait, especially, if there are only small differences.

From the initial philosophizing about the gait, substantiated methods for analysis were developed and new professions emerged. These methods include photography, film and video cameras and a variety of sensors. There

1. Introduction

is no longer a limitation to the verbal description of the gait (verse). The technical possibilities to investigate the gait in terms of physical parameters are given.

1.1. The Importance of the Gait

The human gait has a huge impact on the well-being, quality of life and the daily routine. Even small impairments cause changes in the daily routine. Going up or down the stairs, moving an object, getting up or walking a straight line - all these things become more difficult. A decrease of mobility is also a decrease in the quality of life. Lundh, Nasic, and Riad describe, that fatigue and quality of life is influenced in adults, who suffers from Cerebral Palsy (CP), with impaired walking capacity [2]. How strong these influences are, shows the Austrian assessment regulation [3]. Disabilities up to 50 percent are possible with a shortened leg or a deficit of the knee (Table 1.1). The examples given are only a brief excerpt of the document, the entire list can be found using the link of "*Anlage zur Einschätzungsverordnung*" [3].

The gait pattern provides a lot of information that can change, depending on the situation. The velocity of a person decreases with increasing age, for example. Besides such age-related discrepancies, there are other influences that affect the gait:

- Injuries

1.1. The Importance of the Gait

Table 1.1.: Deficits and the corresponding degree of disability from the Austrian assessment regulation for a shorten leg and an impaired knee. [3]

No.	Shorten Leg	Disability	Knee	Disability
	cm	%	degree of impairment	%
1	< 3	10	low, unilaterally	10 - 20
2	3 - 8	20 - 40	medium, unilaterally	30
3	> 8	50	heavy, both feet	50

- Impaired motor control/muscle weakness
 - Abnormal joint mobility
 - Sensory disorders
 - Pain
 - Limbic-emotional causes
- Diseases, such as
 - Parkinson's
 - Arthritis
 - Multiple Sclerosis
 - Cerebral Palsy

Proper treatment requires an in-depth investigation that identifies the deficits, which leads to help provided by a physical therapy, a surgery or mobility aids. Previously and during the treatment, examinations give information about the health status. Multiple systems for gait analysis are available.

1. Introduction

1.2. Technical Application

For the treatment as well as for the clinical monitoring, a mobile, small and easy to use system would be an advantage. Such a system would be an important tool to support physiotherapists and medical doctors in the daily routine. The impaired gets an enrollment and can practice or train at any time and place. The tedious way to the health care center is eliminated. Integration into eHealth¹ or mHealth² is conceivable. Pairing with other devices via the Internet of Things (IoT) becomes possible. An opportunity to fulfill all these points is provided by a gait analysis system using IMU. An IMU consists of triaxial orthogonal accelerometers, gyroscopes and magnetometers.

The use of IMU in measurement technology is widespread and due to the decreasing sizes, there are also applications in the medical field. Of particular interest is the musculoskeletal system and the locomotion. A simple task, which is supported in nearly every new smartphone, is the step counter or the step detection. Gait pattern identification based on template matching [4], using gait acceleration, or spatio-temporal parameters, measured with a gyroscope [5], are other examples. Especially for the Parkinson's disease, there are many research approaches and possible interpretations of the gait [6] [7] [8] [9] [10]. The measurement of the angles in the spatial directions

¹eHealth or e-health is the application of information and communications technologies for healthcare

²mHealth is an abbreviation for mobile health and describes the support for public health and the practice of medicine by mobile devices.

1.3. Market Analysis

and the distinction of the individual gait phases are important. For this purpose, evaluations and tests between different systems were carried out [11] [12] [13] [14].

1.3. Market Analysis

Table 1.2 shows some companies which provide gait analysis systems based on IMU (total list of the 28 companies can be found at Table A.1). Most of them provide spatio-temporal parameters for the analysis. Only a few can detect the gait phases during a normal human gait (1, 4 and 6 in Table 1.2). Others again, are more interested in the area of sports and the prevention of injuries (3), character animation or industrial applications (5). The gait analysis is not limited to the IMU, there are a variety of other technologies from various manufacturers.

Table 1.2.: Excerpt of the IMU-based gait analysis systems available on the market.

No.	Company	Product	Homepage
1	BTS Engineering	G-Walk	www.btsbioengineering.com
2	Microgate	Gyko	www.microgate.it
3	Innovators	IMeasureU	www.imeasureu.com
4	MindMaze	GaitUp	www.gaitup.com
5	xsens	MTi 1-series	www.xsens.com
6	Hasomed	RehaGait	www.rehagait.de

1. Introduction

1.4. Motivation

A short excerpt of Akhtaruzzaman, Shafie, and Khan [15] overview of the common gait analysis systems is shown in Table 1.3. Motion capture systems, as the state of the art [16] and the golden standard, are not portable and need a while to adjust for the measurement. Compared to an IMU-based system, which is easy to use, small and ready for home-care.

Table 1.3.: Gait analysis technologies [15].

No.	Classification	Technology
1	Independent Systems	Motion Capture Cameras
2		Optoelectronic System
3		Inertial Systems
4		Electrogoniometer
5	Partially independent system	Gait Mat/Pressure Mat
6		Force shoes
7		Magnetic System
8		Acoustic Tracking System
9	Nonindependent Systems	Force Plates Mechanism
10		Electromyography
11		Electroencephalography
12		Medical Imaging Technique
13	Hybrid technology	Combination of Systems from above

A physical therapist cannot recognize all pathologies of the patient during

1.5. Objective

a single walk or gait. The IMU-based system will support the visual examination of the therapist/doctor and delivers a great benefit, due to the spatio-temporal values and the subdivision of the gait cycle. With the help of the measured values the identification of pathologies of the impaired should be possible. Based on the analysis, recommendations for the treatment can be made. An accurate system is required for the evaluation. In this context, accuracy means that the system provides reproducible values that has the lowest possible error compared to a selected reference system. Furthermore, the system is not limited to the examination room and the small examination area, compared to an optical system. Other advantages are the shorter examination times, the lower costs of the system and the use in real life environment becomes possible. This also results in a relief for the patient during the examination. In the area of real-time application, an application for detecting "freezing"³ would also be conceivable. Therefore, it is important to evaluate and quantify the parameters and the accuracy, to create a solid basis for further implementation.

1.5. Objective

A quantitative evaluation of a system, consisting of two Motionsensors (Tyromotion GmbH, Graz, Austria) and an algorithm⁴, which determines the

³The sudden and unpredictable inability to continue or start moving, on people who suffers on Parkinson's disease.

⁴Developed by the Control Systems Group of the Technical University at Berlin

1. Introduction

spatio-temporal parameters and provides the subdivision into the individual gait phases, and a reference system should be made. The reliability and accuracy of the provided system should be interpreted. For the quantitative evaluation a software must be programmed, which connects to the Motion-sensor, record the data and compare with the results from the reference system. The system to be compared to is a Rehawalk (zebris Medical GmbH, Isny, Germany). It is widely used, easily accessible and combines a treadmill with integrated force plates. The force distribution during the gait is well described in various literature and can therefore be helpful for the analysis. With the help of the descriptive and the inferential statistics, the entities will be evaluated and compared. A significance level of $\alpha = 0.05$ is used for the statistical inference.

2. Background

2.1. Inertial Measurement Units (IMU)

An IMU combines an accelerometer, a gyroscope and a magnetometer in one electronic device. Most common devices support three-dimensional (3D) measurements, that means one accelerometer/gyrometer/magnetometer along each axis of that device. The definition of the axis is based on the flight dynamics and are known as roll, pitch and yaw. They describe the angles of rotation in the 3D-space about the center of mass ([Figure 2.1](#)). All in one, the IMU measures the specific force, the angular rate or the surrounding magnetic field that occur to a body. There are two main types of IMU:

- Stable platform IMU: The sensors are fixed on an inner stabilized platform, with the help of a gimbal mounting it is freely movable in space. Three positioning motors, each at a suspension, are controlled in a way, that the rotational movement can be compensated. An expression for the orientation are the actuating variables of the motors.

2. Background

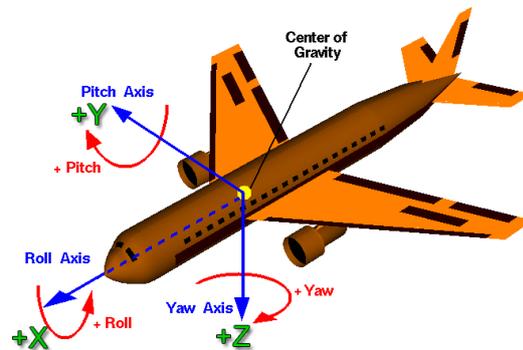


Figure 2.1.: Axes of a plane, adopted to the IMU. [17]

- Strapdown IMU: The sensors are permanently connected to the device, housing or frame. Return values during linear acceleration or rotational motion.

Typical application for IMU are:

- Electronic devices
 - Camera
 - Mobile phones
 - Tablet computers
- Robots
- Aircrafts
- Rockets
- Unmanned Aerial Systems (UAV)
- Cars
- Rehabilitation
- ...

2.1. IMU

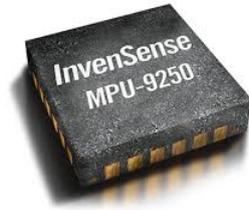


Figure 2.2.: MEMS designed as IMU. [18]

Depending on the application type, the performance of the IMU will be chosen. The most accurate and stable equipment is reserved for the military and is not available for other areas. Most commonly are the inexpensive and tiny Micro-Electro-Mechanical Systems (MEMS). The appearance corresponds to the casing of integrated circuits (Figure 2.2). Therefore, implementing and soldering to a board can be done easily. For each sensor type there are a variety of technologies available. These thesis is limited to the MEMS.

2.1.1. Accelerometer

In detail, the accelerometer measures the rate of change of the velocity. The values given in g (gravity (g); $1g \approx 9,81 \frac{m}{s^2}$). Or in other words, it measures the proper acceleration relative to the free fall. A skydiver, which holds an IMU, falling towards to earth measures an acceleration of zero, compared to a book laying on a desk which measures a relative acceleration of $9,81 \frac{m}{s^2}$.

In MEMS the sensor is using a spring-mass-system made of silicon. The acceleration is measured indirectly with the change of the capacity between

2. Background

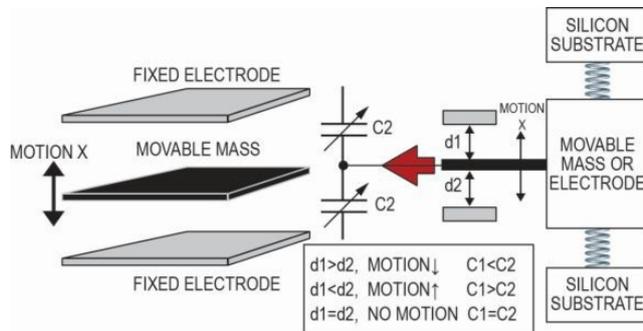


Figure 2.3.: Operation principle of an acceleration sensor. [19]

a movable mass attached to a spring and fixed electrodes (Newton's second law). Comparing the capacities and the distances (between the mass and the electrodes) using $C = \epsilon * \frac{A}{d}$, provides information about the acceleration. Figure 2.3 illustrates a system of a movable mass and two electrodes. The sensitivity range lies between 100 mg to ten μg for accelerometers.

2.1.2. Gyroscope

Orientation and/or the angular velocity can be measured with the gyroscope, the result is a value in $\frac{\circ}{s}$ or $\frac{\text{rad}}{s}$. Imagine a roundabout which is spinning once each second. An attached IMU, in particular the gyroscope, measures a value of about $360 \frac{\circ}{s}$ or $2\pi \frac{\text{rad}}{s}$. Different devices with a sensitivity from $0.1 \frac{\circ}{h}$ to $0.001 \frac{\circ}{h}$ are available.

Similar structure to the acceleration sensor. In comparison, the resonating mass of the gyroscope is also attached to a spring, but with an offset by

2.1. IMU

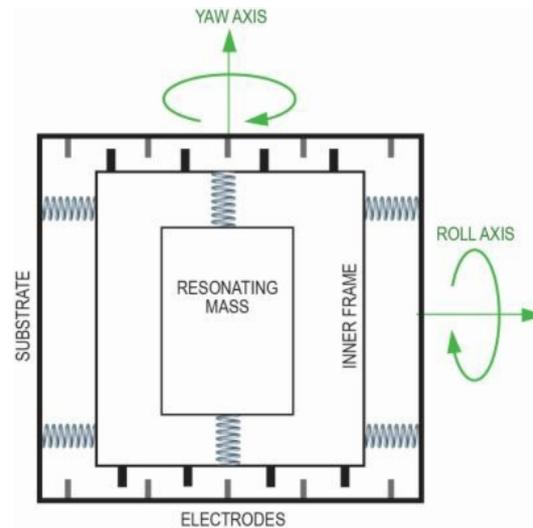


Figure 2.4.: Schematic structure of a gyroscope. [19]

90 degrees from the direction of movement. In that way, the Coriolis force¹ can be determined with the measurement of the capacity change between substrate and electrode (Figure 2.4).

2.1.3. Magnetometer

The magnetometer measures the magnetism in Tesla (T). Specifically, it can determine the direction, strength or relative change of a magnetic field. A simple example is a compass, which measures the magnetic field of the earth.

¹The Coriolis force is an inertial force, which deflects a moving body across the direction of movement, if it is described relative to a rotating reference system.

2. Background

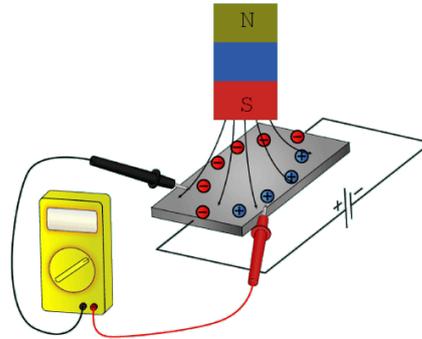


Figure 2.5.: Description of the Hall effect with a conductive plate in the closed circuit. [20]

Most of the MEMS using the Hall effect to detect the magnetic field. Therefore, a conductive plate is integrated into an electrical circuit (Figure 2.5). The electrons move from one side of the plate to the other. A magnetic field near the plate will deflect the electrons. As a result, the electrons are separated from the positive charges in the plate. Measuring the voltage between the long sides of the plate leads to a voltage depending on the strength and direction of the magnetic field.

2.2. Communication

A Bluetooth interface is used for the communication between IMU and software. Therefore, a Bluetooth module is used in combination with the IMU. After pairing the devices with the PC and the use of the default configuration (Baudrate: 19200, eight Data-bits, one Stop-bit and without Parity-bit), data transfer is possible. Different commands, described in a communication

2.2. Communication

Table 2.1.: Excerpt of the IMU communication protocol. “x” for any positive value.

No.	Byte				Description
	Start	Control	Data1	Data2	
1	85	8	o	n	vibration n: number of impulses
2	85	10	x	x	stop sending process
3	85	31	x	x	send predefined values continuously (5 s)

protocol (Table 2.1), controls the data transfer. Each command contains four bytes of positive values.

According to the command, a different number of bytes are received after the sending process. To understand these values, the information of Table 2.2 and Table 2.1 are necessary (Table 2.2 expand Table 2.1 by the answer of the sensor). Sending command number three from Table 2.1 yields to the 24 bytes answer of line three of Table 2.2. In this special case, it will continue to transmit until either five seconds elapse or the abort command is sent (Table 2.1 number 2). For a longer period, the command must be resent before five seconds has elapsed. Other commands, for example, lead to an answer with a different number of bytes. Still others do not return a value. Only eight data bits can be sent along the interface, so a word² is split up to one lower (“l”) and one higher (“h”) byte. A look at Table 2.2 indicates this at number three, where the variables are extended by these

²valid for all data types with more than 8-bit.

2. Background

Table 2.2.: The Motionsensors byte answer of the request. The line numbers correspond to Table 2.1 and the dependent command. “l” indicates the low and “h” the high byte of one word, “bat” is the charge of the accumulator and “misc” contains eight single bits to the status query.

No.	Receiving Bytes	Description
1	0	No answer
2	0	No answer
3	24	255, 255, force_l, force_h, pitch_l, pitch_h, roll_l, roll_h, yaw_l, yaw_h, acc_pitch_l, acc_pitch_h, acc_roll_l, acc_roll_h, acc_yaw_l, acc_yaw_h, gyro_pitch_l, gyro_pitch_h, gyro_roll_l, gyro_roll_h, gyro_yaw_l, gyro_yaw_h, bat, misc

letters. Furthermore, the order of the bytes correlate to that in the table, which is important for the back translation.

2.3. Gait Analysis

To understand the evaluation and the differences between the IMU-based and the Rehawalk reference system, the basics of gait analysis are important. The main parts are discussed shortly. [Figure 2.6](#) shows picturesque the

2.3. Gait Analysis

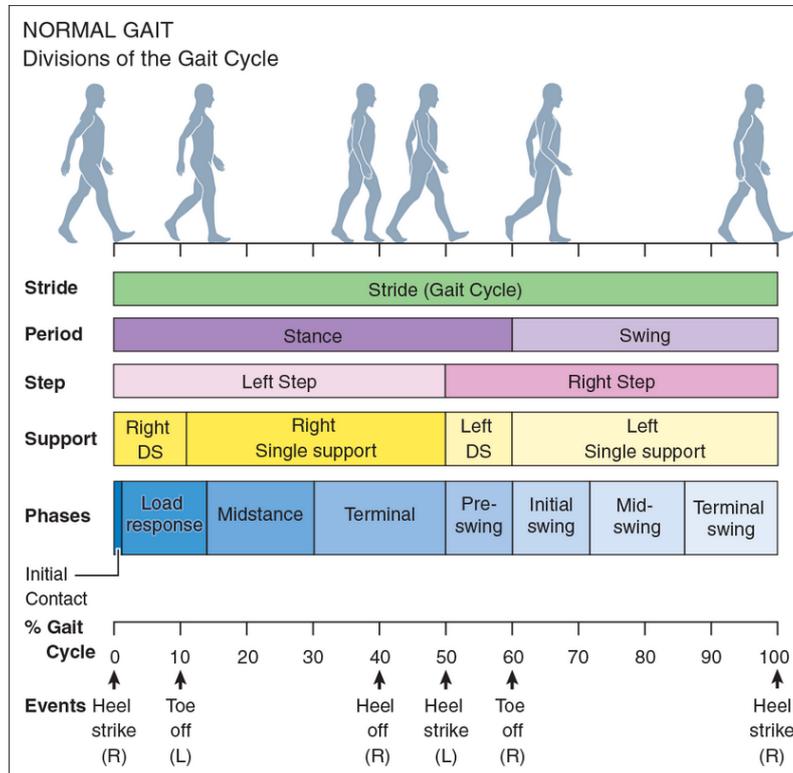


Figure 2.6.: Divisions of a human normal gait cycle [22].

classification of the normal human gait. Of particular importance are the events at the bottom of the picture. A stride or a Gait Cycle (GC) begins with the heel contact of the left foot, for example, and ends with the next heel contact of the same foot. In comparison, a step is the distance from the left to the right heel contact (Figure 2.7) [21].

To be able to quantitatively evaluate the values (IMU against Rehawalk), reference values are necessary (Table 2.3). Another important thing is the sequence of the foot support to detect individual phases during stance

2. Background

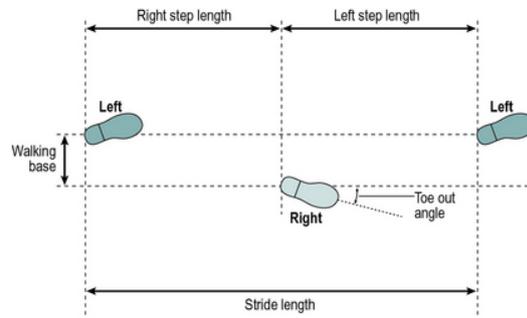


Figure 2.7.: Definition of a gait cycle/stride [23].

(Figure 2.8). These gait patterns can distinguish between humans.

Beginning with the Calcaneograde³ touching the floor, also known as the heel strike (Figure 2.6), ensuing assisted through the sole source (Figure 2.8, Loading Response (LR)). The Plantigrade⁴ posture is introduced with the forefoot contact and terminates the heel-only support period (Figure 2.8, transition from LR to Mid-Stance (MSt)). Heel rise changes the mode of foot support to the Digigrade⁵ (Figure 2.8, Terminal-Stance (TSt)). The end of the stance phase is indicated with the Unguigrade⁶. The toes being the last segment to lift off the ground (Figure 2.8, Pre-Swing (PSw)) [21]. Figure 2.9 establishes the connection between the individual phases of the gait and the pressure distribution of the foot.

The main joints in the foot with the major functional significance (Figure 2.10,

³Calcaneograde_{lat.} = Heel Support

⁴Plantigrade_{lat.} = Foot-Flat (FF) Support

⁵Digigrade_{lat.} = Forefoot Support

⁶Unguigrade_{lat.} = Toe Tips

2.3. Gait Analysis

Table 2.3.: Values for the intervals of a single Gait Cycle (GC) [21].

No.	Interval			Description
	Start	Stop	Duration	
	%			
1	0	2	2	Initial Contact, IC
2	2	12	10	Loading Response, LR
3	12	31	19	Mid-Stance, MSt
4	31	50	19	Terminal-Stance, TSt
5	50	62	12	Pre-Swing, PSw
6	62	75	13	Initial-Swing, ISw
7	75	87	12	Mid-Swing, MSw
8	87	100	13	Terminal-Swing, TSw

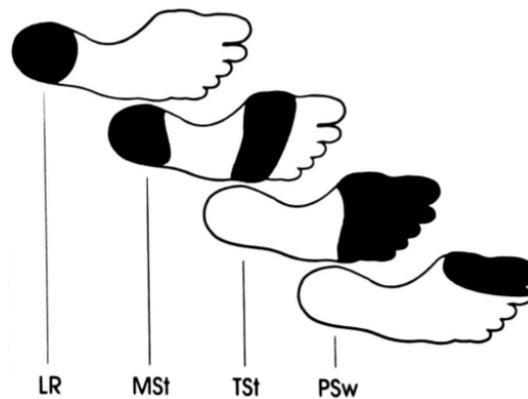


Figure 2.8.: Sequence of the foot support during stance [21]. “LR” is the Loading Response, “MSt” the Mid-Stance, “TSt” the Terminal-Stance and “PSw” the Pre-Swing

2. Background

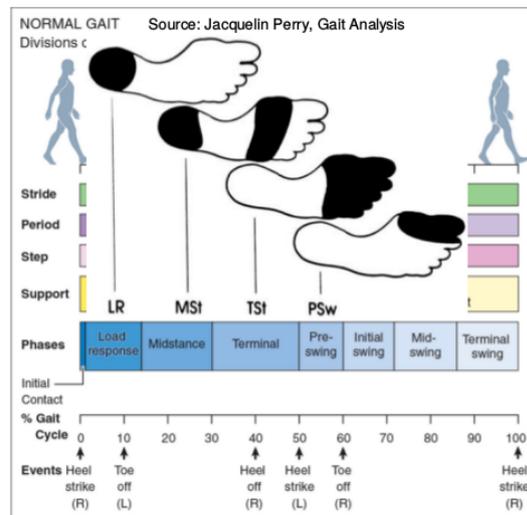


Figure 2.9.: Connection between the gait phases and the pressure distribution [21] [22].

dyed black) are the Subtalar (ST), Midtarsal (MT) and the Metatarsophalangeal (MTP). The Subtalar action adds coronal and transverse plane mobility to the sagittal plane function available at the ankle. The mobility of the Midtarsal is customarily just observed and provides information about the vertical alignment of the tibia, talus and calcaneus, between initial contact and terminal stance. The Metatarsophalangeal joint changes the orientation (Figure 2.11) between initial contact (25° dorsiflexion) and pre-swing (55° plantar flexion) [21].

2.3.1. Spatio-Temporal Parameters

The spatio-temporal parameters include values for pitch, roll, Maximum Lateral Deviation (MLD) and Maximum Z Position (MZP). With Figure 2.1

2.3. Gait Analysis

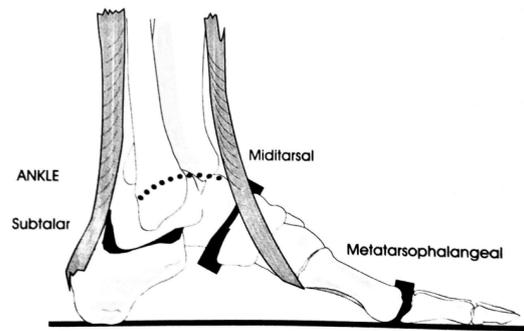


Figure 2.10.: Major joints in the foot during the gait [21].

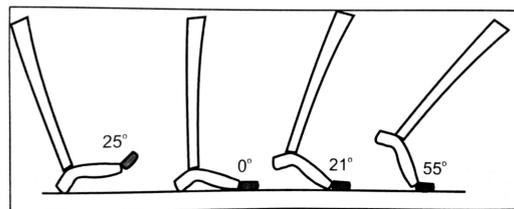


Figure 2.11.: Joint motion during the stance phase [21].

2. Background

pitch and roll are explained, whereas MLD describes the largest deviation to the walking base ([Figure 2.7](#)) during the swing phase. MZP represents the maximum value of the foot lift during the swing phase. Both values are given in centimeters.

3. Methods

The following chapters describe the used hard- and software, the introduction of the patients/subjects and ends with the description of the measurements and the according calculations.

3.1. Hardware

The used devices, the so called Motionsensor (Tyromotion GmbH, Graz, Austria), is an IMU-based sensor. It is delivered as standard with the Pablo¹ system. The whole system consists of the Pablo-handle, the charger, the Motionsensor, the loop straps and the Bluetooth USB adapter. Except of the handle, the full list of the hardware is shown in [Table 3.1](#).

¹Hand/arm therapy and assessment device. The system allows training of all types of grasping, tracking the grip force and the range of motion [24].

3. Methods

Table 3.1.: Used hardware from Tyromotion.

No.	Quantity	Serial number	Type	Manufacturer
1	1	PMRo-2017-131	Motionsensor	Tyromotion
2	1	PMRo-2017-132	Motionsensor	Tyromotion
3	2	-	Loop straps	Tyromotion
4	2	-	Charger	Tyromotion
5	1	-	Bluetooth dongle	Hama



Figure 3.1.: Tyromotions IMU-based Motionsensor.

3.1.1. Motionsensor

Nine Degrees Of Freedom (DOF) are supported by the Motionsensor (Figure 3.1). Three axis each for acceleration, gyroscope and magnetometer. In Addition, the device offers the possibility for haptic feedback via an integrated vibration engine. Furthermore, a Red-Green-Blue Light-Emitting-Diode (RGB-LED) provides information about the device status. Details about the color coding can be found in Table 3.2.

Table 3.2.: Explanation of the LED color coding.

No.	Color	LED State	Description
1	Red	Flashing	Low battery level
2		Continuous	Error occurred
3	Green	Flashing	Device is online, but not connected
4		Continuous	Device is online and connected
5	Blue	Flashing	Device is charging
6		Continuous	Device is charged

In addition, it supports autonomous operation and wireless data exchange via a Bluetooth connection for up to four hours.

3.1.2. InvenSense MPU-9250

The Motion sensor comes with a MPU-9250 (InvenSense Inc., Jan Jose, USA) “MotionTracking” device. The integrated circuit uses 16-bit analog/digital converter (ADC) for each axis of each of the three sensors. The sensitivity of the gyroscope and the accelerometer can be chosen. Possibilities are:

- Gyroscope: ± 250 , ± 500 , ± 1000 or $\pm 2000 \frac{\circ}{s}$
- Accelerometer: ± 2 , ± 4 , ± 8 or $\pm 16g$

Only the magnetometer is fixed to a sensitivity of $\pm 4800 \mu T$. In [Table 3.3](#) the selected sensitivities and the depending scale factors are listed. To determine the sensors real value in SI-units, the sensitivity scale factor is used. Besides,

3. Methods

Table 3.3.: Settings and used scale factors for the InvenSense MPU-9250. *The accelerometer settings changed during the work.

No.	Sensor	Sensitivity	Sensitivity Scale Factor
1	Gyroscope	$\pm 2000 \frac{\circ}{s}$	$16.4 \frac{LSB}{\frac{\circ}{s}}$
2	Accelerometer*	$(\pm 2g) \pm 8g$	$(16384 \frac{LSB}{g}) 4096 \frac{LSB}{g}$
3	Magnetometer	$\pm 4800 \mu T$	$0.6 \frac{\mu T}{LSB}$

the device has a Digital Motion Processor (DMP), which processes the data from the sensors in-side, as well as from third-party sensors connected to it. The DMP acquires data, do the calculations and writes it to predefined registers. The MPU-9250 works with an internal sample frequency of 200 Hz. However, the firmware of the Micro Controller Unit (MCU) only reads out these registers, via I^2C (Inter-Integrated Circuit²), at 60 Hz.

3.2. Software

For the measurement recording, analysis, visualization and data manipulation different software is used. The main task is done with Unity (Unity Technologies, San Francisco, USA), a Game-Engine. With Unity, Visual Studio (Microsoft, Redmond, USA), the recommended Integrated Development Environment (IDE) is also installed. Scientific PYthon Development

²Is a synchronous, multi-master, multi-slave, packet switched, single ended serial computer bus

3.2. Software

EnviRonment (Spyder, Spyder developer community), as a way for data analyzing and evaluation, is used. [Figure 3.2](#) shows the individual parts of the project. The boxes with the blue background color indicates the existing parts, whereas the green and gray boxes are the parts to be developed.

3.2.1. Unity Framework

In order to be able to record measured data, a corresponding program had to be written. With the help of Unity, Visual Studio and C# as programming language, the design of the framework is done. A simple and clearly designed Graphical User Interface (GUI) should be the result. Major points (compare with [Figure 3.2](#)) for the development of the framework are the

- GUI and the navigation structure,
- Communication between the application and the Motionsensor,
- Data recording,
- Analysis of the entities and
- Representation of the analysis.

Unity

At the beginning, the tutorials from the Unity homepage were reprogrammed to familiarize with the development environment. The individual lessons are well structured and give an insight into the comprehensive

3. Methods

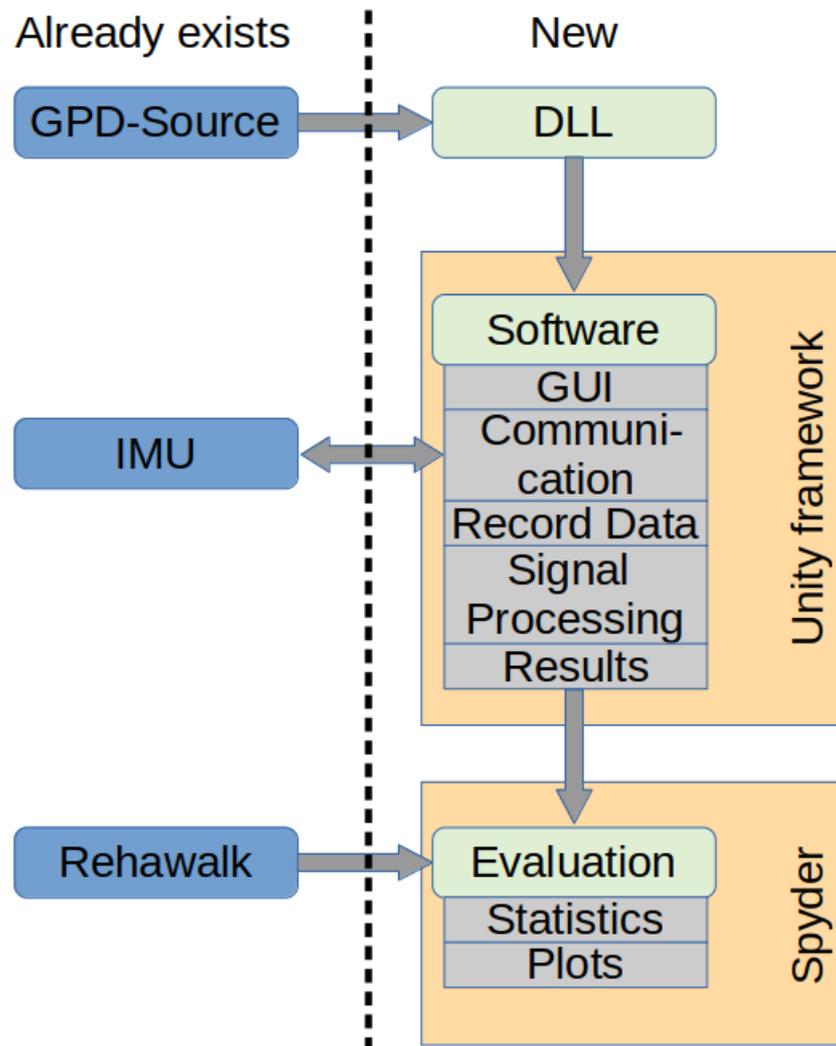


Figure 3.2.: Composition of the software. Blue indicates the existing code/hardware/results and the green and gray boxes are the things to be developed. “GPD” is the source code for the Gait Phase Detection, “GUI” is the Graphical User Interface and “DLL” is the Dynamic-Linked Library.

3.2. Software

possibilities of Unity. While working on the tutorials, the idea was born to use the Inertial Measurement Units (IMU) as game controller for one of the games. But first the communication interface must be programmed.

Communication

The implementation of the communication interface between the Unity environment and the Motionsensor caused some problems. A simple test script, which connects to the devices and change the status LED worked, others, which send a command and expect some receiving bytes, did not. After a few tests and a long unsuccessful debugging, these scripts were tested in the Visual Studio environment (without Unity). Everything worked well, so the bug must be somewhere in the Unity environment. Examining the problem shows that Unity is blocking the events provided by the C# class. With the Unity-packages of Wilches [25] and some adaptations, the problems were fixed. Additionally, the *"APICompatibilityLevel"* in the player settings must be changed from *".NET 2.0 Subset"* to *".NET 2.0"*. Now Unity is forced to use the full library, including the class *"SerialPort"*, which enables such communication.

Before proceeding with the GUI, the game "Roll a Ball" was modified so that the game control is done using the IMU. The task is to control a ball and collect items on the field. The IMU behaves like a joystick and controls the direction and speed of the ball. The more the IMU tilts to one side, the

3. Methods

faster it moves in the game. In addition, the assignment of the axes of the IMU can be checked.

GUI

Typically, buttons are used to navigate in the program. A smooth transition between the scenes³ is achieved by fading in and out. In a persistent scene, the settings and data are saved as well as loaded. Furthermore, it controls the serial ports of the Motionsensors and thus the communication. To establish a connection to one device, the COM-port of a paired Motionsensor must be chosen. Followed by the link connection, the device is ready to use. It is important to ensure that both sensors are connected. By using [Table 2.1](#) the application can communicate with the devices. Generally speaking, the application makes a request and the Motionsensor responds. Another button starts the measurement and record the data. After finishing the measurement, the collected data are saved to a Comma-Separated Values (CSV) file.

File Browser and Dialog Box

The file browser allows an easy and fast navigation through the system and to the desired save location. Surprisingly, the build-in file browser of the

³In Unity a scene file is a unique level, which contains the environments and menus of the game.

Unity development environment does not work in an executable program. Therefore, a separate had to be programmed. Parts of the code are also used for the implementation of the message windows (warnings and errors).

Signal Processing

To use the values from the IMU, some signal processing is necessary. [Table 3.4](#) provides a detailed list about the receiving bytes. In case of command number three in [Table 2.1](#) each answer packet starts with two consecutive bytes with a value of 255 (trigger). Note, that the integers of all other values are shifted to prevent 255. Looking at line number four in [Table 3.4](#) a complete conversion combines the low and high byte to an integer ([Equation 3.1⁴](#)), subtracts the shift of 32768 Least Significant Bit (LSB) and finally divide it by the sensitivity scale factor ([Table 3.3](#)) of the acceleration sensor ([Equation 3.2](#)). The goal of this sequence is to obtain SI-units and avoid further calculations.

$$x_{10} = 256 \cdot \text{byte}_{High_2} + \text{byte}_{Low_2} \quad (3.1)$$

x_{10} : Integer
 byte_{High_2} : High-byte
 byte_{Low_2} : Low-byte

⁴The multiplication with 256 corresponds to a bit shift with eight places to the left

3. Methods

Table 3.4.: Conversion details of the raw IMU values of the command number three in Table 2.1.

No.	Receiving Bytes	Values / Variables	Type	Conversion Details
1	2	255, 255	byte	trigger, indicates the beginning of one data packet
2	2	force	integer	not in use, equals zero
3	each 2	pitch, roll, yaw	integer	shifted by 18000 LSB, sensitivity in 0.01°
4	each 2	acc_pitch, acc_roll, acc_yaw	integer	shifted by 32768 LSB
5	each 2	gyro_pitch, gyro_roll, gyro_yaw	integer	shifted by 32768 LSB
6	1	bat	byte	battery charge: bat $\in \{0, 1, \dots, 100\}$ %
7	1	misc	byte	single status bits

$$y = \frac{x_{10} - s}{x_{ssf}} \quad (3.2)$$

x_{10} : Integer

s : Shift

x_{ssf} : Sensitivity Scale Factor

y : Converted value

Dynamic Link Library (DLL)

The algorithm, to determine the gait phases, was developed by the Control Systems Group at the TU Berlin. To integrate the code into Unity, a DLL was created. The DLL is necessary because it was programmed in a different language (C++, managed code). Therefore, minor adjustments to the source were necessary. Problems arose both when creating and integrating the DLL into Unity. During the creation, special attention had to be paid to the correct use of the pointer of the calling function. Because of the unmanaged code, the calling script must use the "*AllocHGlobal*" method (Marshal class) to allocate memory for the pointer, store it into a variable and pass it to the function. Another issue includes the DLL build options. In the case of a 64-bit Unity environment, the DLL must conform to the system architecture (64-bit built).

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3.2.2. Gait Analysis

The recorded gait data are transferred to the DLL and evaluated. The DLL provides a way to determine the following four phases of the gait:

- 0: Foot Flat (FF)
- 1: Pre-Swing (PSw)
- 2: Swing (Sw)
- 3: Loading Response (LR)

[Figure 3.3](#) shows details about the detection. Each phase ends with a special event. Starting point is the rest phase or Foot-Flat (FF) (0), that ends with the heel off. The state changes to Pre-Swing (PSw) (1) and ends with the toe-off. Now, the state changes to swing (2). Swing is completed with the initial contact of the heel, followed by the state change to Loading Response (LR) (3). If the entire foot is in contact with the ground, the LR ends and the new phase is the initial phase, FF (0). This sequence repeats until the gait is completed. In addition, temporal and spatial parameters are determined ([Table 3.5](#)), depending on the orientation of the IMU. Parameters as well as the phases are calculated separately per foot. The evaluation is completed with the representation of the results in the application.

The source code includes a data file for testing. To check the functionality of the DLL, these data were copied to a CSV-file. Finally, the call of the DLL, with this file as input parameter, should coincide with the outcome of the source.

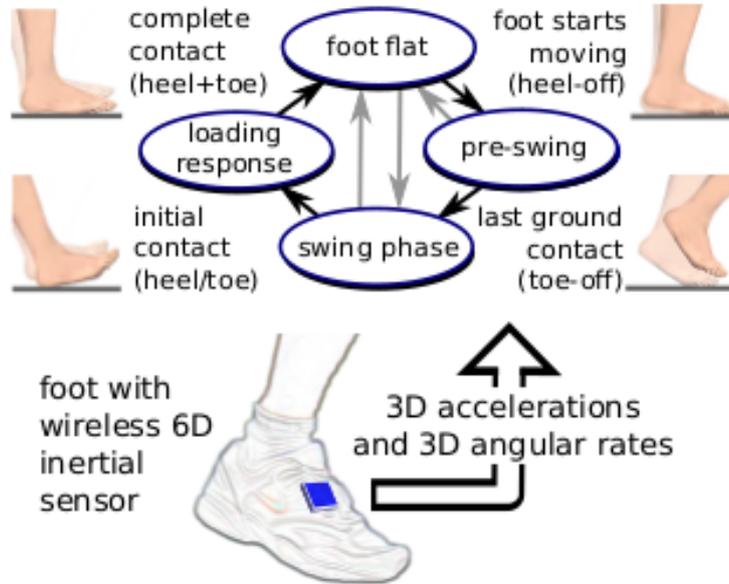


Figure 3.3.: Detection of the four phases during human gait, using an IMU-based system [26].

Table 3.5.: Additional parameters of the gait analysis, calculated for each leg.

No.	Parameter	Unit	Additional Information
1	Gait Velocity	$\frac{km}{h}$	
2	Cadence	$\frac{Steps}{min}$	
3	Pitch	$^{\circ}$	min. and max.
4	Roll	$^{\circ}$	min. and max.
5	Stride Length	m	
6	Max. Lateral Deviation	cm	
7	Max. Z Position	cm	

3. Methods



Figure 3.4.: Rehawalk system with integrated protective device [27].

3.3. Measurement

For comparison, the Rehawalk (zebris Medical GmbH, Isny, Germany; [Figure 3.4](#)) is used. The System combines a treadmill with an integrated pressure measurement technology. It supports a gait analysis based on the pressure distribution during the gait. The adjustable velocity of the treadmill is a good review point. Using the Rehawalk as the reference system, the values can be checked. A list of the used zebris soft- and hardware can be found in [Table 3.6](#).

Table 3.6.: The used zebris hard- and software.

No.	zebris system	Description
1	Hardware	Rehawalk; serial number: 2017-01-17
2	Software	Evaluation software FDM

3.3. Measurement

The decision, to use the zebris system as reference for the accuracy determination of the Motionsensor, is based on the possibility of easy distinguishing between stance and swing phase, the calculation of those, it is widely used and easily accessible. Besides, a special attention is paid to the swing and stance phase.

Unclear is the evaluation of the zebris system in relation of the gait phases. The system provides four phases: LR, MSt, TSt and Sw. A look at [Figure 2.8](#) indicates four phases during stance. Either the TSt phase is summed up with the MSt or the PSw. The IMU code provides also four phases: LR, FF, PSw and Sw. Now, the MSt and the TSt are combined in the FF. Both Systems can determine the stance and the swing phase, thus a comparison is possible.

A few requirements must be met for the measurement. Based on an ethics proposal (University of Graz, GZ. 39/55/63 ex 2017/18), all subjects must be protected against falling, which is done with the protective device of the Rehawalk ([Figure 3.4](#)). All participants are anonymized, numbered and had to perform three walks ([Table 3.7](#)). At the beginning the subject had to walk a couple of minutes on the treadmill, to familiarize with the system. During the walk, a short introduction about the measurement was given. At the beginning and at the end of each measurement, a stand phase for the Motionsensors is required. A typical measurement include the sequence shown in [Figure 3.5](#). Motionsensor and Rehawalk recording and analyzing the data independently but measures the subject at the same time. At the end the results are compared.

3. Methods

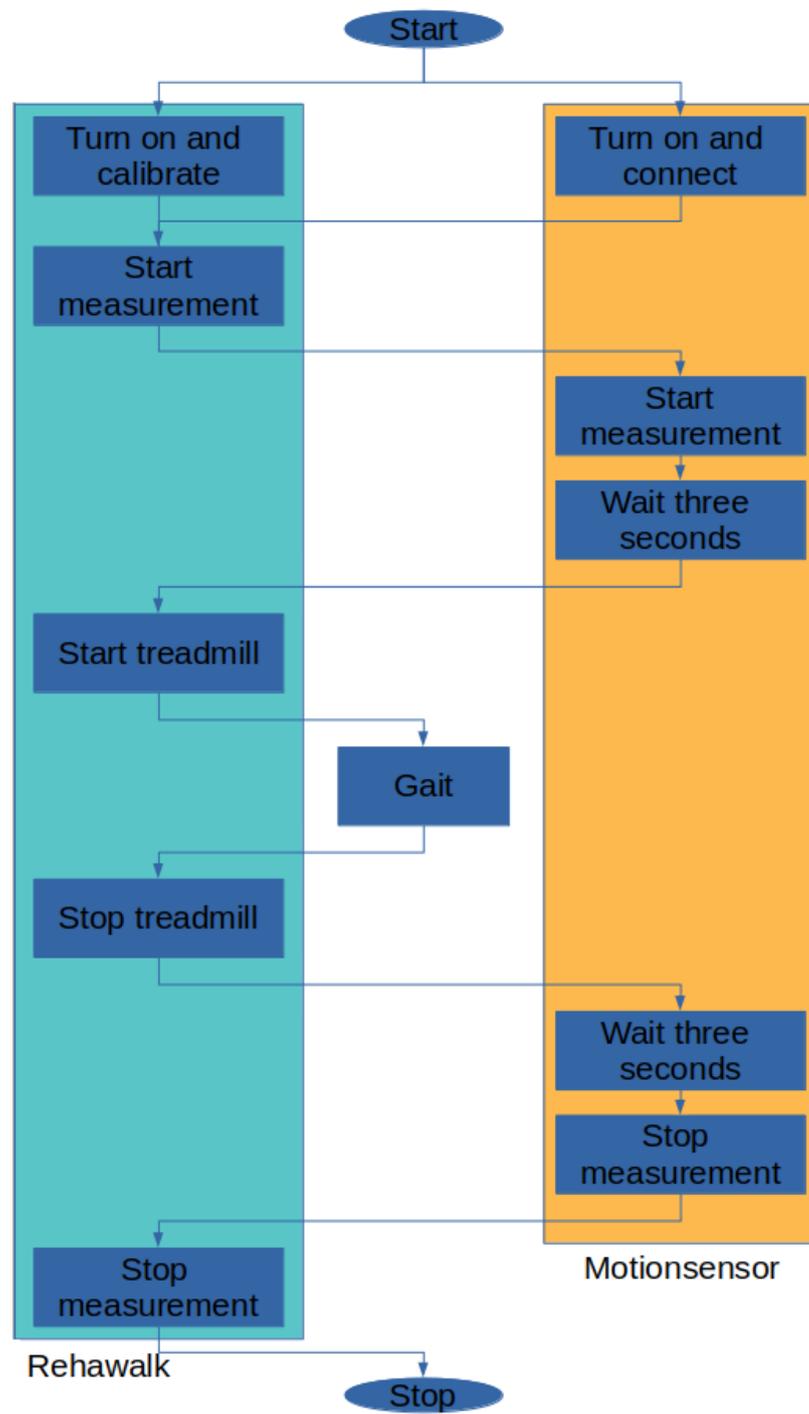


Figure 3.5.: Scheme of a single measurement.

3.4. Data Evaluation

Table 3.7.: List of measurements made.

No.	Velocity	Duration	Impairment
	$\frac{km}{h}$	s	
1	3	90	No, normal gait
2	5	90	No, normal gait
3	3	90	Restriction of the Flexion of the right knee (RF; knee brace), no flexion of the knee is possible

19 subjects of both genders and different ages are members of the test group. The Motion sensors are fixed on the dorsum pedis⁵ of each foot. Subjects were asked to report loosening fixation of the sensors to correct measurement errors. In such a situation, the measurement must be repeated after the attachment has been renewed.

3.4. Data Evaluation

Specified by the nomenclature, the right foot is represented with the green and the left foot with the red color. Figure 3.6 shows an excerpt of the zebris evaluation. Likewise, it indicates the subdivision into the different gait phases. Since the zebris system serves as a reference, the values of the Motion sensors are represented in the same way.

⁵dorum pedis = instep

3. Methods

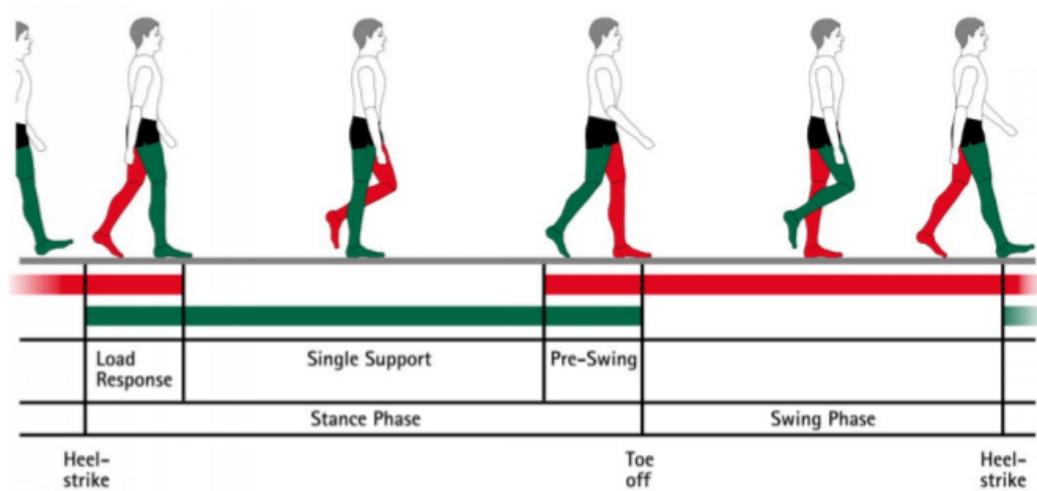


Figure 3.6.: Color representation of a gait cycle of the zebris evaluation, including the phases. Green belongs to the right and red to the left foot [28].

Subsequently, from the individual phases of the stance, the sum (Stance (ST) phase) is calculated. Furthermore, the sum of the cadence from the left and right foot as well as the average of the stride length of both feet was calculated. A precise overview of the comparable values is given in Table 3.8.

3.4.1. Descriptive Statistic

An overview of the measured data is given with Spyder and the Python package *"scipy.stats"* using the function *"describe"*. The result are values for

- Minimum

3.4. Data Evaluation

Table 3.8.: Comparable gait phases. Stance is the sum of LR, MSt and PSw.

No.	Description	Detail
1	Stance Phase	Loading Response in %
2		Mid-Stance in %
3		Pre-Swing in %
4	Swing Phase	in %
5	Stride Length	in cm
6	Cadence	in $\frac{Steps}{min}$
7	Velocity	in $\frac{km}{h}$

- Maximum
- Mean
- Variance
- Standard Deviation
- Skewness and
- Kurtosis.

For the comparison, the differences of the mean values should be given in absolute and relative numbers. Furthermore, box plots are used to visualize the values and for facing the Motion sensor values against the ReWalk.

3. Methods

3.4.2. Inferential Statistics

Due to the paired sample, the t-test is used to compare the mean values between the systems. It is performed with a significance level of $\alpha = 0.05$. Prerequisite for the t-test are the normally distributed differences (d) of the samples, which is why a check is carried out using Shapiro-Wilk test. Based on these results, either a t-test (normal distributed) or a Wilcoxon test (otherwise) is performed.

Shapiro-Wilk normality test

- $H_0: d = 0 \Rightarrow$ The data are normally distributed with a significance level of $\alpha = 0.05$.
- $H_1: d \neq 0 \Rightarrow$ The data are not normally distributed with a significance level of $\alpha = 0.05$.

t-test

- $H_0: \mu_d = 0 \Rightarrow$ The mean values of both systems are equal ($d = 0$) with a significance level of $\alpha = 0.05$.
- $H_1: \mu_d \neq 0 \Rightarrow$ The mean values of both systems are not equal ($d \neq 0$) with a significance level of $\alpha = 0.05$.

Wilcoxon test

- H_0 : The median values of both systems are equal with a significance level of $\alpha = 0.05$.
- H_1 : The median values of both systems are not equal with a significance level of $\alpha = 0.05$.

3.4. Data Evaluation

Of special interest are the spatio-temporal parameters between the measurements of the Motion sensor. The reference is the normal gait with three $\frac{km}{h}$ and the other two walks should be compared with. In detail, the Maximum of the Lateral Deviation (MLD), the Maximum of the Z Position (MZP) and the pitch and roll angles. These values indicate changes in walking behavior.

4. Results

Vicarious for all calculations, five samples for the x-axis of the acceleration were done. It starts with the hexadecimal bytes using [Equation 3.1](#), followed by [Equation 3.2](#) and the sensitivity scale factor number two of [Table 3.3](#). Additionally, the multiplication with 9.81 ($1g = 9.81 \frac{m}{s^2}$) is done to get a the values in SI-units. All other values can be calculated analogously. [Table 4.1](#) is the summary of these calculations.

Testing the DLL with the extracted data from the source, returns the following result of [Figure 4.1](#). Running the source code (data file included), leads to the same result.

4.1. Clipping

During the work, several test measurements were made. In some records, plateaus ([Figure 4.2](#)) were found in the readings of the accelerometer. This behavior indicates, that the end of the measurement range has been reached.

4. Results

Table 4.1.: Calculation of the accelerometer values.

No.	Axis	Hex		Integer	Corrected	Acceleration	
		Byte		Dec	shift	Gravitation	SI
		low	high	LSB	LSB	g	$\frac{m}{s^2}$
1	X	F2	7E	32498	-270	-0.0659	-0.6467
2		1A	7F	32538	-230	-0.0562	-0.5509
3		18	7E	32280	-488	-0.1191	-1.1688
4		27	7E	32295	-473	-0.1155	-1.1328
5		1D	7F	32541	-227	-0.0554	-0.5437

```

#---- LEFT 4 phases ----#
lr med: 9.21053 q1: 9.06177 q3: 9.21053
ff med: 39.0702 q1: 38.1579 q3: 40.3896
ps med: 17.1053 q1: 16.5 q3: 17.1053
sw med: 35.0965 q1: 34.0995 q3: 35.5263
#---- LEFT 4 phases ----#
lr med: 9.21053 q1: 9.06177 q3: 9.21053
ff med: 39.0702 q1: 38.1579 q3: 40.3896
ps med: 17.1053 q1: 16.5 q3: 17.1053
sw med: 35.0965 q1: 34.0995 q3: 35.5263

```

Figure 4.1.: Resulting gait phases (left source code, right DLL) of the integrated file from the source code provided from the TU Berlin. "lr" indicates Loading Response, "ff" Foot-Flat, "ps" Pre-Swing, "sw" Swing, "med" median, "q1" first quartile and "q3" third quartile

4.2. IMU-based Gait Measurement System (Motionsensor)

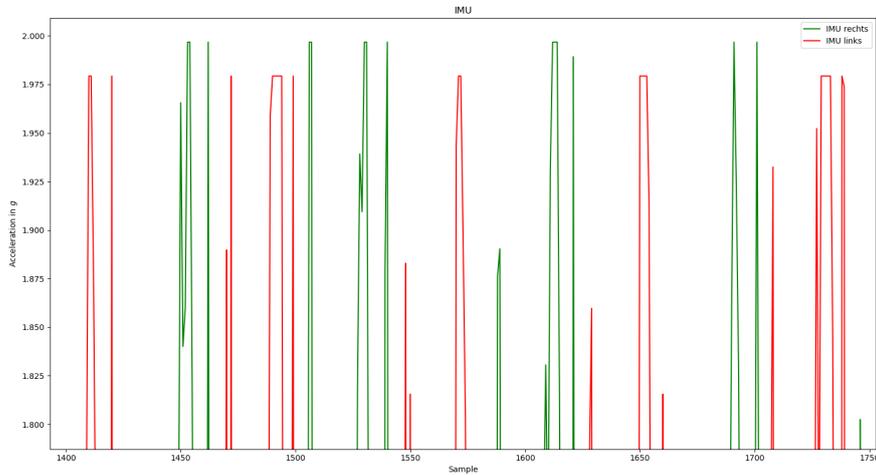


Figure 4.2.: Clipping of the acceleration values of the x-axis.

The so-called "clipping" can be remedied by changing the sensitivity and is associated with a change in the sensitivity scale factor.

4.2. IMU-based Gait Measurement System (Motionsensor)

The representation of the following measured values, of subject one, are representative for all records. [Figure 4.3](#) showing the converted values of the accelerometer. Using the DLL with these data as input, returns the gait phases ([Figure 4.3](#), black line) and the spatio-temporal parameters.

4. Results

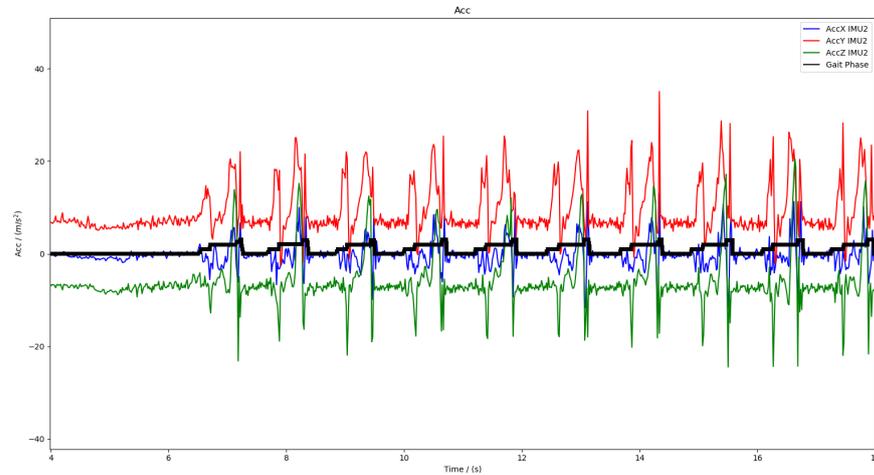


Figure 4.3.: A zoom of the acceleration values, of proband number one, including the gait phases. “0” indicates FF, “1” PSw, “2” Sw and “3” LR.

The starting point for the comparison is [Table 4.2](#). The Stance (ST) phase is the sum of Loading Response (LR), Foot-Flat (FF) and Pre-Swing (PSw). The sum of the cadence and the mean of the stride length were also determined. [Table B.1](#) shows all values of the descriptive statistics.

4.3. Rehawalk System

Analyzing the data recorded with the Rehawalk is performed with the zebris FDM-T-System (zebris Medical GmbH, Isny, Germany). Again, the data for subject one is shown ([Figure 4.4](#)). The complete list with all values of the descriptive statistic can be found in [Table B.2](#).

4.3. Rehawalk System

Table 4.2.: List of measurements made. For each foot, the average and the Standard Deviation (SD) was calculated.

No.	Parameter	Unit	Left		Right	
			Mean	SD	Mean	SD
1	LR	%	9.38702	1.67519	8.43614	2.09426
2	FF		42.2947	3.12881	43.0235	3.70633
3	PSw		13.8678	1.22949	14.2127	1.40889
4	Sw		34.4505	2.01778	34.3276	2.68604
5	Min Pitch	°	-55.6746	3.35311	-56.2534	2.92244
6	Max Pitch		16.597	2.19223	16.9806	2.46181
7	Min Roll		-5.92776	2.85852	-4.02844	1.39125
8	Max Roll		6.52144	2.41063	10.1012	3.39729
9	SL	m	1.01611	0.1	1.0	0.1
10	MLD	cm	4.96735	1.1	4.9	1.2
11	MZP		6.01215	1.2	5.6	1.3
12	Velocity	km/h	2.88802	0.314	2.885	0.334
13	Cadence	Steps/min	47.3707		47.2648	
14	Steps	Quantity	57		58	

4. Results



Figure 4.4.: Result of the zebris analysis of participant one [28].

4.4. Comparison: Motion sensor versus Rehawalk

Altogether, 57 measurements from 19 experimentees, eleven males (21.82 years \pm 2.44) and eight females (19.88 years \pm 0.83) are evaluated. For each of the datasets, the differences between the two systems were calculated (Table 4.3).

An illustrative depiction of the values from all measurements following in the Figure 4.5 to 4.7.

Finally, the largest aberrations from the calculations were searched and wrote to the Table 4.4. The columns indicated with “w/o” are without the measurements of subjects number seven and 17, because those indicate irregularities in the measured values.

4.4. Comparison: Motionsensor versus Rehawalk

Table 4.3.: Calculation of the differences between the Motionsensor and the Rehawalk. Used are the measurements with 3 km/h. “St” indicates the sum of the stance phase (LR + FF + PSw). Cadence is the sum and Stride Length (SL) is the average of both feet.

No.	Parameter	Unit	zebris	IMU	Difference	
					absolute	relative
1	Velocity	km/h	2.9	2.89	-0.01	-0.0041
2	Cadence	Steps/min	93.0	94.64	1.64	0.0176
3	SL	cm	105.0	101.66	-3.34	-0.0318
4	St L	%	66.9	65.55	-1.35	-0.0202
5	St R	%	67.0	65.67	-1.33	-0.0198
6	Sw L	%	33.1	34.45	1.35	0.0408
7	Sw R	%	33.0	34.33	1.33	0.0402

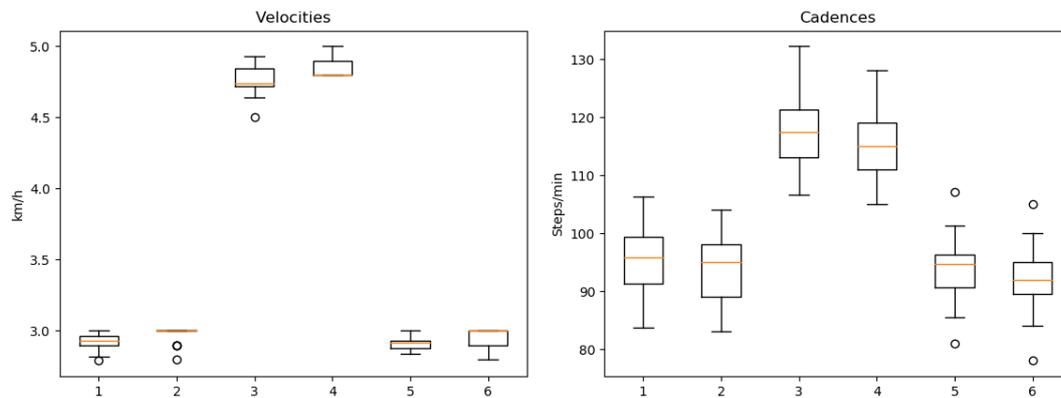


Figure 4.5.: Representation of the velocity (left) and the cadence (right) measurements of the Motionsensor (odd numbers) and the Rehawalk (even numbers).

4. Results

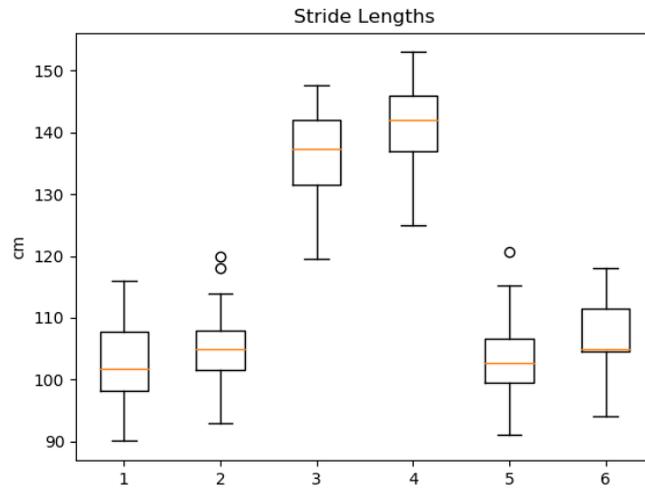


Figure 4.6.: Representation of the Stride Length (SL) measurements of the Motion sensor (odd numbers) and the Rehawalk (even numbers).

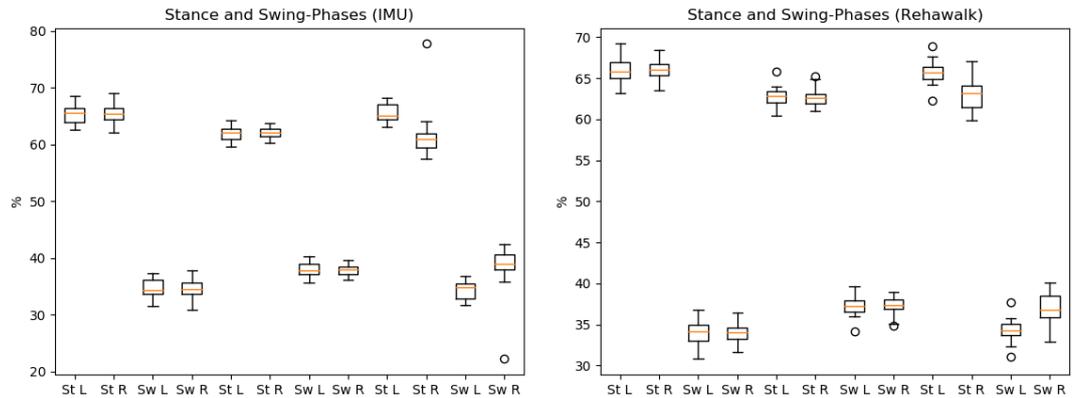


Figure 4.7.: Representation of the stance and swing phase measurements of the Motion sensor (left) and the Rehawalk (right). The first four entries indicate the gait with three km/h , followed by four entries with five km/h and the last four entries with three km/h and the restriction of the flexion.

4.4. Comparison: Motionsensor versus Rehawalk

Table 4.4.: Presentation of the error: Motionsensor against Rehawalk. “w/o” indicates that the calculation was done without the proband number seven and 17.

No.	Parameter	Relative Error					
		$3\frac{km}{h}$		$5\frac{km}{h}$		$3\frac{km}{h}$ RF	
		%	w/o %	%	w/o %	%	w/o %
1	Velocity	-0.016	-0.010	-0.018	-0.014	-0.013	-0.011
2	Cadence	0.017	0.017	0.021	0.021	0.016	0.017
3	SL	-0.027	-0.022	-0.037	-0.032	-0.030	-0.027
4	St L	-0.009	-0.007	-0.011	-0.008	-0.003	-0.007
5	St R	-0.008	-0.007	-0.010	-0.008	-0.019	-0.014
6	Sw L	0.018	0.015	0.020	0.015	0.007	0.014
7	Sw R	0.015	0.014	0.018	0.013	0.036	0.024

4. Results

The results of the Shapiro-Wilk and Wilcoxon or t-test are shown in Table 4.5. The null hypotheses, in case of the Shapiro-Wilk test, must be rejected for a p-value equal or smaller than the significance level $\alpha = 0.05$, meaning that the differences between the Motionsensor and the Rehawalk are significant different from normal distribution. From the output, except of the line numbers ten, 16, 17, 19 and 21, all values are normal distributed. The t-test is applied to these, the exceptions are checked with the Wilcoxon test.

Table 4.5.: Results of the Shapiro-Wilk (normality check) and Wilcoxon (not normal distributed are line numbers ten, 16, 17, 19 and 21) or t-test (all others). "T-Statistic" holds the value of the test-statistic.

No.	Gait	Parameter	Shapiro-Wilk		Wilcoxon/t-test	
			T-Statistic	p-value	T-Statistic	p-value
1	3 km/h	Velocity	0.946	0.331	-2.918	0.009
2	3 km/h	Cadence	0.941	0.273	9.685	0.000
3	3 km/h	SL	0.958	0.542	-6.427	0.000
4	3 km/h	St L	0.949	0.374	-2.452	0.025
5	3 km/h	St R	0.930	0.171	-1.574	0.133
6	3 km/h	Sw L	0.949	0.374	2.452	0.025
7	3 km/h	Sw R	0.930	0.171	1.574	0.133
8	5 km/h	Velocity	0.921	0.116	-4.329	0.000
9	5 km/h	Cadence	0.903	0.056	12.519	0.000
10	5 km/h	SL	0.900	0.048	0.000	0.000
11	5 km/h	St L	0.975	0.869	-3.030	0.007
12	5 km/h	St R	0.946	0.332	-2.331	0.032

4.4. Comparison: Motion sensor versus ReWalk

No.	Gait	Parameter	Shapiro-Wilk		Wilcoxon/t-test	
			T-Statistic	p-value	T-Statistic	p-value
13	5 km/h	Sw L	0.975	0.869	3.030	0.007
14	5 km/h	Sw R	0.946	0.332	2.331	0.032
15	3 km/h RF	Velocity	0.946	0.331	-2.659	0.016
16	3 km/h RF	Cadence	0.860	0.010	0.000	0.000
17	3 km/h RF	SL	0.899	0.047	7.000	0.000
18	3 km/h RF	St L	0.947	0.356	-0.782	0.444
19	3 km/h RF	Ste R	0.665	0.000	26.000	0.006
20	3 km/h RF	Sw L	0.947	0.354	0.784	0.443
21	3 km/h RF	Sw R	0.665	0.000	26.000	0.006

For the t-test, a p-value greater than the significance level of 0.05 implying, that there is a statistical significance, that the mean values of both systems are equal and the null hypotheses can be accepted, otherwise it must be rejected and concluded, that the differences in the mean are not zero (mean values not equal). Table 4.5 shows, that only in the lines five, seven, 18 and 20 the null hypotheses can be accepted for a significance level of $\alpha = 0.05$. The null hypothesis cannot be accepted for the Wilcoxon test either.

Of particular interest are the changes in the spatio-temporal values between the different measurements. Therefore, the gait with three $\frac{km}{h}$ will be the reference and the other two gaits are these with pathologies. Table 4.6 indicates the differences between the three $\frac{km}{h}$ and three $\frac{km}{h}$ with Restriction

4. Results

of the Flexion of the right knee (RF) for subject one. The biggest differences can be found in ST, Swing (SW), minimum Pitch and minimum Roll. The same results are provided by the other datasets too.

Table 4.6.: Measurement of subject one: Comparison between three $\frac{km}{h}$ and three $\frac{km}{h}$ with Restriction of the Flexion of the right knee (RF).

No.	Parameter	Unit	Left	Right
1	LR	%	-0.579	-1.380
2	FF		-0.945	-0.826
3	PSw		1.317	-1.681
4	St		-2.580	-3.069
5	Sw		0.206	3.888
6	Min Pitch	°	-1.910	18.990
7	Max Pitch		-3.763	-5.965
8	Min Roll		2.330	-11.517
9	Max Roll		1.773	1.608
10	SL	cm	-0.013	-0.030
11	MLD		-0.065	0.830
12	MZP		-0.635	-0.988
13	Velocity	$\frac{km}{h}$	0.053	-0.006
14	Cadence	$\frac{Steps}{min}$	1.506	1.330

Again, the Shapiro-Wilk test is performed to check the normality of the values (Table 4.7). According to the results the t-test or the Wilcoxon test

4.4. Comparison: Motionsensor versus Rehawalk

(Table 4.7, number four) was applied.

Table 4.7.: Normality check with the Shapiro-Wilk and the depending Wilcoxon or t-test.

The gait values with three $\frac{km}{h}$ are used as the reference.

No.	Parameter	Shapiro-Wilk		Wilcoxon/t-test	
		T-Statistics	p-value	T-Statistics	p-value
$5 \frac{km}{h}$					
1	Min Pitch	0.973	0.832	0.973	0.832
2	Max Pitch	0.904	0.057	0.904	0.057
3	Min Roll	0.945	0.330	0.945	0.330
4	Max Roll	0.835	0.004	0.835	0.004
5	MLD	0.970	0.771	0.970	0.771
6	MZP	0.978	0.914	0.978	0.914
7	Steps Left	0.936	0.220	0.936	0.220
8	Steps Right	0.908	0.069	0.908	0.069
$3 \frac{km}{h}$ RF					
9	Min Pitch	0.970	0.774	0.970	0.774
10	Max Pitch	0.967	0.719	0.967	0.719
11	Min Roll	0.959	0.560	0.959	0.560
12	Max Roll	0.927	0.150	0.927	0.150
13	MLD	0.972	0.814	0.972	0.814
14	MZP	0.936	0.219	0.936	0.219
15	Steps Left	0.957	0.513	0.957	0.513
16	Steps Right	0.943	0.299	0.943	0.299

5. Discussion

The testing procedure is not the best possible case. For both systems, the start and stop is defined in the stance phase. It took a long period of time from the start of the treadmill to the predefined velocity. Acceleration as well as the deceleration process is included in the measurement of both systems, so the evaluation should be correct. Regarding the further work, only the part with constant speed should be used for the evaluation, to get more accurate values.

5.1. Software

Most of the work was spent on implementing the software. The troubleshooting was sometimes very difficult and led to unconventional solutions. Although all provided a part to correct the bugs but were also very cumbersome and time-consuming. For example, the Dynamic Link Library (DLL) was tested with combinations of different operating systems (Linux,

5. Discussion

Windows 7, Windows 10), Integrated Development Environment (IDE) (Visual Studio, Eclipse), compilers and target systems to track down the errors. Finally, all bugs have been fixed and an executable program implemented.

The occurrence of "clipping" [Figure 4.2](#) shows that the measuring range was too small. The logical consequence was the change in sensitivity and the depending sensitivity scale factor. The recommendation for IMU-based systems is $\pm 5g$, as this value is not realizable with the MPU-9250 ([subsection 3.1.2](#)), $\pm 8g$ was chosen. According to the new settings, these values had to be adjusted in the software.

The implementation of the "Roll a Ball" game proved useful as it determined that the axes of the IMU did not coincide with the orientation of the motion sensor. The default mounting of the IMU provides that the arrow on the housing points in the forward direction of the gait. With the help of this knowledge, the axes assigned correctly.

5.2. IMU versus Zebris

Generally, the evaluation of the values between Motionsensor and Rehawalk ([Table 4.4](#)) shows a deviation less than four percent. The highest values are located at the stride lengths. The measurements of subjects seven and 17 are those with the highest deviation. For subject seven the source of defect was in the loosening of fixation. A comparison of the measured values from

5.2. IMU versus Zebris

subject seven and 17 indicates that the fixation could also have eased on subject 17. Consider only the phases, the error is less than two percent.

Only four parameters out of 21 (from the comparison, [Table 4.5](#)) shows a statistical significance that the mean values of both systems are equal. It cannot be concluded that the mean values of both systems match, because the significances depend to different, unrelated parameters.

Noteworthy is the accuracy in determining the speed. Only a deviation from $0.01 \frac{km}{h}$ ([Table 4.3](#)) for walk one (three $\frac{km}{h}$) and for all a maximum of $0.30 \frac{km}{h}$ (1.69 %). A look at [Table 4.4](#) shows, that the higher deviations correlates to the higher walking speed of five $\frac{km}{h}$. Regarding to the micro-controllers sample frequency of 60 *Hz* and the translation from the continuous to discrete time, the error is negligibly small. Is the sampling rate compared to other papers with a similar topic, for example Jimenez et al. [29] and Seel, Landgraf, and Schauer [26] using 100 *Hz*, Fakharian, Gustafsson, and Mehrfam [30] and Mair et al. [31] using 120 *Hz* and Favre et al. [32] using 240 *Hz*, the recommendation is a sample frequency of 100 *Hz*.

Similar to the speed, the cadence has a small aberration ([Table 4.4](#), number two). Compared to the Zebris evaluations, the results ([Table 4.3](#)) are within a deviation of two steps.

Differently is the behavior with the stride length. A maximum deviation of more than eleven centimeters or approximately four percent ([Table 4.4](#), number three), causes a high error in the results. With the assumption that

5. Discussion

the values are integrated twice and the rather slow sampling rate, the high aberration can be explained.

The stance and the swing phases shows a small deviation of about two percent. However, the swing of the right foot is almost twice as high. With a maximum aberration of 3.6 percent (Table 4.4, number seven) from the Rehawalk system for a gait with three $\frac{km}{h}$, a more detailed investigation is necessary. A look at the evaluation shows, that one possible reason could be the attachment or assignment of the sensors. No statement can be made about it, if only the values of the Motionsensors are considered. Useful is the report of the zebris system, there, the first step can be evaluated and assigned to the foot. For further examinations special attention should be taken that the sensors are not interchanged.

The other parameters such as the maximum of the lateral deviation, the maximum z position and the pitch/roll (minimum and maximum) cannot be evaluated with the help of the zebris system. To compare these values an optical system will be needed, for example a Vicon-System (Vicon Denver, Centennial, USA). A quantitative evaluation of these values is not possible.

The assumption that the toe out angle (Figure 2.7) will change with increased speed could not be determined, because there are no significant changes. On the one hand Table 4.6 showing differences in the measurements, but on the other hand the statistical calculation shows that the differences of the mean values are the same for the used α of 0.05 (Table 4.7). Only number four

shows, that the medians are not equal. Thus, the null hypotheses cannot be rejected.

A look at [Figure 4.7](#), indicates a difference between the measurements of the normal gaits (three and five $\frac{km}{h}$) to the measurements with the restriction of the flexion of the right foot (also three $\frac{km}{h}$). It can be seen, that with the blocking of the knee, the phases of the right foot changes. The swing phase increases, whereas the stance is decreasing. In addition, the figures show that the stance phase decreases with increasing speed, which reflects the physiological behavior. If only one patient is observed ([Table 4.6](#)), it can be seen that not only the gait phases change, but also the foot angles during the swing phase. With which one can infer the selected method of the subject to overcome the blocking of the knee. Quantitative evaluation would require the use of an optical system or visual confirmation from a therapist/doctor.

A different representation of the values, as the chosen with the minimum and maximum values, will be helpful. For the identification of pathologies, especially for the dorsiflexion and the plantar flexion, a plot of the foot angles against time with the representation of the gait phase is recommended. From this, specific abnormalities can be determined with respect to [Figure 2.11](#).

Another limiting factor is the communication via Bluetooth. Sometimes there are troubles with the communication and the data transfer between

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IMU and the application. To avoid these problems, tests are made within a range of five meters.

The interpretation of the gait, using the source investigated, can be outlandish for non-technicians. For a therapeutic application, a redesign is required. The same applies for the gait phases. The used system, to subdivide the gait into four phases is not state of the art and should be substituted with the recommended five phases [21]. An accurate five phases system includes LR, MSt, TSt and PSw for the stance phase and a swing phase. For this purpose, both legs may no longer be considered separately.

5.3. Conclusion

This work is the starting point of the development of a gait analysis system, based on IMU. The investigation of the Motion sensor in combination with the code, provided by the control group at TU Berlin, shows a high correlation to detectable and comparable parameters of the zebris ReWalk system. The system provides values with sufficient accuracy to determine the individual gait phases of the human gait and to use it for support in clinical application. Despite the outlier, the mean of the measurement error is within a four percent deviation. The individual phases are detected with less than two percent deviation. The statistical evaluation shows no significance of the mean values for a selected $\alpha = 0.05$. Differences between normal gait and pathologic gait (restriction of the flexion in the knee) are detectable, but

5.3. Conclusion

does not show a statistical significance for the spatio-temporal parameters using an $\alpha = 0.05$. With the measuring system, the stance and swing phases can be determined. A more accurate subdivision of the phases (five phases system) can improve the evaluation even more.

6. Outlook

The next steps include the expansion of the algorithm to detect the five phases during gait, followed by the evaluation. Further work on the spatio-temporal parameters and evaluation with an optical system. Implementation of an easy to understand visualization. After finishing these points, a simple, easy to use and inexpensive alternative for the gait analysis is available. The system would be useful both clinically and in home care. Additionally, the haptic feedback can be used to interact with the user. Therefore, an application on the phone with real-time support would be conceivable.

Appendix

Appendix A.

Attachments to the Introduction

Table A.1.: Overview of IMU-based gait analysis systems and IMU hardware.

No.	Company	Product	Homepage
1	BTS Engineering	G-Walk	www.btsbioengineering.com
2	Microgate	Gyko	www.microgate.it
3	Innovators	IMeasureU	www.imeasureu.com
4	MindMaze	GaitUp	www.gaitup.com
5	Nexonar	LPMS-B2	www.nexonar.com
6	Telocate	μ IMU	www.telocate.de
7	xsens	MTi 1-series	www.xsens.com
8	x-io Technologies	x-IMU	www.x-io.co.uk
9	zFlo	iSen (STT-IBS)	www.zflomotion.com

Appendix A. Attachments to the Introduction

No.	Company	Product	Homepage
10	Noraxon	MoCap	www.noraxon.com
11	BioSensics	LEGSys	www.biosensics.com
12	Technaid	Tech IMU V4 Series	www.technaid.com
13	stt-Systems	STT-IWS	www.stt-systems.com
14	Delsys	Frigno-Avanti	www.delsys.com
15	Motion Workshop	MotionNode	www.motionnode.com
16	Yost	3-Space sensor	www.yostlabs.com
17	Hasomed	RehaGait	www.rehagait.de
18	Inertial Labs	IMU-P	www.inertiallabs.com
19	Live Performance Research	LPMS-USBAL	www.lp-research.com
20	Notch	Notch Pioneer kit	www.wearnotch.com
21	NexGen	I2M Motion Tracking	www.nexgenergo.com
22	Cometa	WaveTrack Inertial System	www.cometasystems.com
23	Kinvent	K-Sens	www.k-invent.com
24	Biosyn Systems	F.A.B.	www.biosynsystems.com
25	Centaure Metrix	Locometrix	www.centaure-metrix.com
26	Vectornav	VN-100 SMD	www.vectornav.com

Appendix B.

Extension of the results

B.1. Descriptive Statistic

Table B.1.: Descriptive statistic of the IMU.

No.	Parameter	Min	Max	Mean	Var	SD	Skewness	Kurtosis
1	v	2.79	3.00	2.92	0.00	0.05	-0.95	0.42
2	Cad	83.67	106.36	95.14	35.50	5.96	-0.19	-0.56
3	SL	90.06	115.97	102.88	50.88	7.13	0.24	-0.70
4	St L	62.59	68.52	65.30	2.92	1.71	-0.10	-0.81
5	St R	62.19	69.13	65.42	2.82	1.68	0.16	-0.10
6	Sw L	31.48	37.41	34.70	2.92	1.71	0.10	-0.81

Appendix B. Extension of the results

No.	Parameter	Min	Max	Mean	Var	SD	Skewness	Kurtosis
7	Sw R	30.87	37.81	34.58	2.82	1.68	-0.16	-0.10
8	v	4.50	4.93	4.76	0.01	0.11	-0.49	0.07
9	Cad	106.57	132.20	117.20	41.30	6.43	0.30	-0.15
10	SL	119.60	147.70	135.87	58.56	7.65	-0.54	-0.53
11	St L	59.64	64.28	61.99	1.70	1.30	-0.07	-0.91
12	St R	60.32	63.83	62.09	1.03	1.01	-0.11	-0.90
13	Sw L	35.72	40.36	38.01	1.70	1.30	0.07	-0.91
14	Sw R	36.17	39.68	37.91	1.03	1.01	0.11	-0.90
15	v	2.84	3.00	2.91	0.00	0.05	0.24	-0.62
16	Cad	80.89	107.11	93.72	32.20	5.67	0.03	0.87
17	SL	91.05	120.61	104.00	45.65	6.76	0.64	0.66
18	St L	63.16	68.23	65.55	2.27	1.51	0.40	-1.06
19	St R	57.55	77.77	61.72	18.50	4.30	2.85	8.48
20	Sw L	31.77	36.84	34.45	2.27	1.51	-0.40	-1.06
21	Sw R	22.23	42.45	38.28	18.50	4.30	-2.85	8.48

Table B.2.: Descriptive statistic of the Rehawalk.

No.	Parameter	Min	Max	Mean	Var	SD	Skewness	Kurtosis
1	v	2.80	3.00	2.97	0.00	0.06	-1.98	2.91
2	Cad	83.00	104.00	93.58	34.26	5.85	-0.25	-0.82

B.1. Descriptive Statistic

No.	Parameter	Min	Max	Mean	Var	SD	Skewness	Kurtosis
3	SL	93.00	120.00	105.68	45.56	6.75	0.51	-0.04
4	St L	63.20	69.20	65.91	1.95	1.40	0.39	0.12
5	St R	63.50	68.40	65.94	1.42	1.19	-0.15	-0.23
6	Sw L	30.80	36.80	34.09	1.95	1.40	-0.39	0.12
7	Sw R	31.60	36.50	34.06	1.42	1.19	0.15	-0.23
8	v	4.80	5.00	4.85	0.00	0.06	0.65	-0.54
9	Cad	105.00	128.00	114.82	36.14	6.01	0.15	-0.43
10	SL	125.00	153.00	141.11	47.43	6.89	-0.34	-0.06
11	St L	60.40	65.80	62.71	1.61	1.27	0.29	0.35
12	St R	61.00	65.20	62.75	1.45	1.20	0.67	-0.34
13	Sw L	34.20	39.60	37.29	1.61	1.27	-0.29	0.35
14	Sw R	34.80	39.00	37.25	1.45	1.20	-0.67	-0.34
15	v	2.80	3.00	2.95	0.00	0.06	-0.85	-0.27
16	Cad	78.00	105.00	92.23	33.66	5.80	-0.27	1.00
17	SL	94.00	118.00	107.16	36.92	6.08	0.01	-0.13
18	St L	62.30	68.90	65.76	2.16	1.47	-0.07	0.56
19	St R	59.90	67.10	62.96	3.84	1.96	0.13	-0.60
20	Sw L	31.10	37.70	34.24	2.16	1.47	0.07	0.56
21	Sw R	32.90	40.10	37.04	3.84	1.96	-0.13	-0.60

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