# PROJECT DELIVERABLE REPORT

## Project Title:

Advanced personalised, multi-scale computer models preventing osteoarthritis

SC1-PM-17-2017 - Personalised computer models and in-silico systems for well-being

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**Revision History**

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| Version | Date | Responsible | Description/Remarks/Reason for changes |
|---|---|---|---|
| 1.0 | 01/10/2018 | UPAT | First draft version. |
| 1.1 | 29/11/2018 | UPAT | Version for internal review |
| 1.2 | 04/12/2018 | UPAT | Internal review issues: (1) missing comparative analysis of existing hardware and software solutions; (2) better links to requirements and other WPs are needed |
| 1.3 | 09/12/2018 | UPAT | Major changes |
| 1.4 | 11/12/2018 | UPAT | Final version |

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**Abbreviations**

| Short | Long |
|---|---|
| **ADC** | Analog to Digital Conversion |
| **AHRS** | Attitude and Heading Reference Systems |
| **AI** | Artificial Intelligence |
| **AMOLED** | Active-Matrix Organic Light-Emitting Diode |
| **AOSP** | Android Open Source Project |
| **API** | Application Programming Interface |
| **AR** | Augmented Reality |
| **BIOS** | Basic Input/Output System |
| **BNC** | Bayonet Neill–Concelman |
| **CoR** | Collection of Rewards |
| **CPU** | Central Processing Unit |
| **DDR4 SDRAM** | Double Data Rate Fourth-Generation Synchronous Dynamic Random-Access Memory |
| **DOF** | Degrees of Freedom |
| **DoW** | Description of Work |
| **DSP** | Digital Signal Processor |
| **DSS** | Decision Support System |
| **ECG** | Electrocardiography |
| **EEPROM** | Electrically Erasable Programmable Read-Only Memory |
| **EMG** | Electromyography |
| **EOMs** | Equations of Motion |
| **eSIM** | Embedded Subscriber Identity Module |
| **FPS** | Frames per Second |
| **GPs** | Golden Points |
| **GPS** | Global Positioning System |
| **GPU** | Graphics Processing Unit |
| **GRF** | Ground Reaction Forces |
| **HD** | High Definition |
| **HDD** | Hard Disk Drive |
| **HDMI** | High-Definition Multimedia Interface |
| **HDR** | High-Dynamic-Range |
| **HDTV** | High-definition television |
| **HMD** | Head Mounted Display |
| **HPU** | Holographic Processing Unit |
| **HUD** | Heads-Up-Display |
| **ID** | Inverse Dynamics |
| **IDE** | Integrated Development Environment |
| **IK** | Inverse Kinematics |
| **IMMU** | Inertial-Magnetic Measurement Unit |
| **IMU** | Inertial Measurement Unit |
| **JRA** | Joint Reaction Analysis |
| **KAM** | Knee Adduction Moment |
| **LE** | Low Energy |
| **LED** | Light-Emitting Diode |
| **NGIMU** | Next Generation Inertial Measurement Unit |

| | |
|---|---|
| **OA** | Osteoarthritis |
| **OLED** | Organic Light-Emitting Diode |
| **OSC** | Open Sound Control |
| **PC** | Personal Computer |
| **PG** | Performance Goal |
| **PIL** | Personalized Intervention Layer |
| **RAM** | Random Access Memory |
| **SD** | Standard Definition |
| **SDI** | Strap-Down Integration |
| **SDK** | Software Developer's Kit |
| **SIM** | Subscriber Identification Module |
| **Si-OLED** | Silicon-Based Organic Light-Emitting Diode |
| **SO** | Static Optimization |
| **SoC** | System on Chip |
| **SPs** | Simple Points |
| **TTL** | Transistor-Transistor Logic) |
| **USB** | Universal Serial Bus |
| **USB-C** | Universal Serial Bus Type C |
| **VR** | Virtual Reality |
| **VRAM** | Video Random Access Memory |
| **WP** | Work Package |

# 1 Summary

The scope of this deliverable is to present the architecture design of the personalized intervention services in accordance with the Description of Work (DoW) related to WP7. The development of these services aims to delay the progression of osteoarthritis (OA) using gait intervention techniques and comprehensive games that will enhance the physical activities of the users. The purpose of the gait intervention approach is to retrain the gait habits of individuals in a personalized manner resulting in reduced knee pain. In this deliverable, we will present two solutions of the gait intervention framework, namely an immobile version that can be deployed in laboratories that are well equipped with kinematic and kinetic measurement systems, and a mobile version which can be used outside the lab. The purpose of the game intervention framework is to motivate and engage users to increase their physical activities. Everything will be integrated into a personalized guidance system that will blend information from other areas of the OACTIVE project (e.g., WP3 multiscale mechanistic modelling) and use this information to construct the patient intervention strategy. The framework will also provide all necessary means for the direct and intuitive visualization of all clinical, physiological and behaviour parameters. The aim is to identify the best methods, to provide knowledge to users in an optimal way (e.g., real-time visual information, warnings, alerts, vibrotactile feedback, processes, experiences, personalized stimuli, etc.). The basic module will be equipped with two different front-ends targeting the two different end-user groups of OACTIVE project. The patient front-end will be equipped with intuitive visualizations (based on visual analytics techniques) of specific only parameters understandable by the patient, while more complex representations and visualizations will be included in the front-end of the clinician. The implemented visual analytics techniques will deliver different perspectives on specific sub-graphs of the correlated data and models to provide role-specific (personalised) and goal-oriented representations of the medical information.

# 2 Introduction

The objective of WP7 is to perform an analysis of hardware devices and software tools, design the game hardware and software, develop the game-like gait retraining framework and the game itself and generate the OACTIVE personalized intervention services, the intelligent information processing system and Decision support System (DSS) module. The tasks can be broken into four objectives:

- Perform an analysis of the Augmented Reality (AR) hardware and software tools
- Implement the software framework
- Develop the games and gait retraining framework
- Interface with the personalized intervention services, information processing, visualization and DSS

In this deliverable, the architectural design of the different tasks described in the WP7 will be presented, including a detailed analysis of state-of-the-art hardware devices and software tools to be used for the game prototypes implementation. We will start with an overview of the whole system and then we will present the details of the individual tasks.

## 2.1 Architecture Overview

A high-level overview of the OACTIVE system was previously presented in D2.3, which describes the reference architecture of the system and its components including the interdependencies of the different modules. Here, we describe in more detail the components of the Personalized Intervention Layer (PIL), which allows the patient to experience the treatment as more enjoyable, resulting in greater motivations, engagement, and training adherence. Figure 1 depicts the overall architecture diagram of the PIL, as well as its relationship with the rest of the system. The purpose of the PIL is to combine sensory input and subject-specific data, originating from WP3 and other related WPs, and to compose the personalized gait retraining and rehabilitation strategy that will be implemented through the interaction of the subject with the feedback devices.

The computational modeling layer will provide subject-specific information, based on principles of physics and physiology, that will be used to define the appropriate personalized intervention strategy. The input data may also originate from other activities of the OACTIVE project, e.g., biomarkers, behavior, hyper-modeling, etc., described in WP3-6. Appropriate abstraction barriers (data abstraction) through big data analytics and machine learning techniques provided by WP6, will be used to decouple the implementation from the input data representation in order to provide a modular and extendable design.

The sensory information, that can originate from a variety of sensor devices, such as Inertial Measurement Units (IMUs), motion capture systems, Electromyography (EMG), ground reaction plates, and ground reaction smart shoes, will be analyzed, stored, processed and compared against the optimal performance dictated by the Decision Support System (DSS). Convenient interfaces should be created so as to enable the support of multiple, heterogeneous devices. The information must be synchronized using data synchronization techniques, such as network time protocol. Appropriate filtering and preprocessing will be applied to refine and remove any artifacts (e.g., noise) that can negatively affect the processing phase. Finally, the necessary information required by the personalized intervention module will be extracted.

The personalized intervention module will fuse sensory and other information in order to define the subject specific strategy. Multiple rehabilitation strategies will be specified based on the expert's knowledge and results from WP3. This module will choose the most appropriate strategy of action according to the provided information in real time.

The differences between the sensed and desired indicators will be encoded and transmitted to the user in an intuitive manner through the feedback devices, using the AR and non-AR logic. For example, one may present the information obtained from the real time simulation, e.g., joint reaction loads, knee abduction moment, muscle force distribution, foot progression angles, etc., using simple projection devices or smart glasses. Vibrotactile feedback can be used to stimulate the user so as to correct and adapt his/her gait habits during training. The feedback device interfaces must be defined in order to enable seamless integration of the PIL to facilitate possible future extensions, nonetheless, the concept of the intervention logic will be affected by the devices that are to be used.

All the available metrics will be stored, analyzed and presented to the users of the system using visual analytics, in order to engage the subjects and provide clinicians with useful performance indicators that can be used to evaluate and modify the intervention methods. The purpose of this module is to extract information from the vast amount of data and to present it to the user in a perceptive manner.

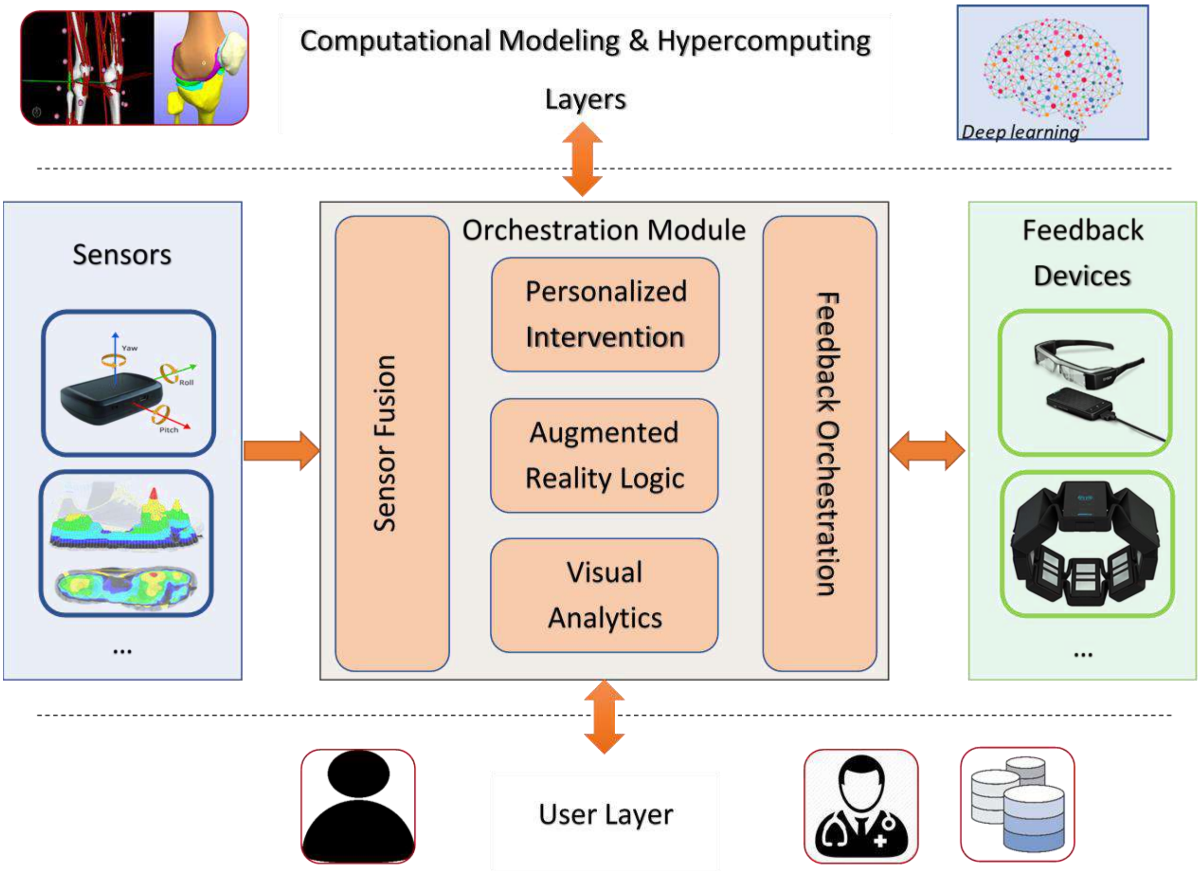



Figure 1 Architecture diagram of the personalized intervention through augmented reality layer and its relationship the rest of the system.

## 2.2 Outline

The outline of this deliverable is provided below:

- The Requirements Identification and Analysis section, establishes the main steps of the co-design process that will guide the design and implementation of the AR system for gait retraining.
- The Gait Retraining section presents and overview of the gait intervention system, followed by the hardware and software analysis and the design of the immobile and mobile gait retraining solutions.

The Nonetheless, an AR system can be employed to substitute the screen where the game is viewed. The purpose of using an AR system is to improve the interaction of the user with the application/game and enhance the user experience. By displaying virtual objects in the real environment, not only the user will better comprehend how to walk effectively, but also creates and environment that excites the user, stimulates his senses and thus motivating him to seek again for this "unique" experience.

As in the previous case, the JRA from the data and statistics from the wearable devices as well as the AI DSS must operate in real time, so that the participant has instantaneous feedback in order to closely follow his "virtual trainer" or to alarm him immediately whether he is executing an irregular – dangerous activity.

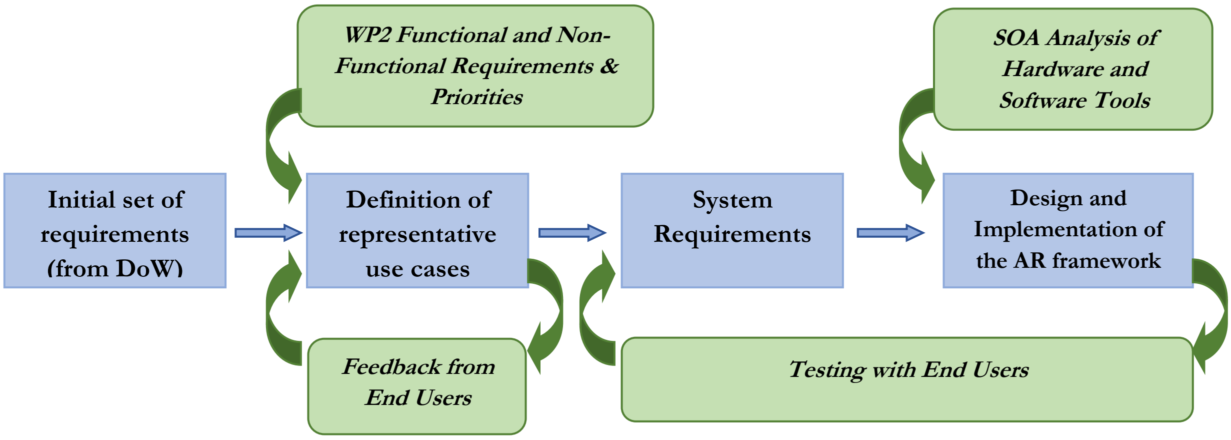
Additional objectives that we need to set for the design of the games are:

- The games must be easily understandable and they must not require any long technical manual or specialized tutorials. Users must quickly start trying them, and they must feel confidence and security while they play.
- The purpose of each game separately is to become a "habit" for the user. This means that users must come back on a regular or daily basis to commit mostly repetitive playing.
- Continuously give meaning, interest, and excitement to the users so they never become boring to play the games.
- The user must not feel anxious about the technology and the games must seem simple and without lags. For example, a simple progress bar is a great feature to help the users get through the waiting process. This makes it very clear what the site wants patients to do, how doing it, and emotionally rewards them for doing it.
- Achievements should be awarded for sticking to the desired behavior.
- Badges should be awarded for long-term performance after hitting some cumulative target.
- Levels as a measure of progress, with gradual "unlocking" of game features (e.g. advanced analytics, comparative evaluations), designed to engage the player in the early stages of the game.

- Information Visualization section provides more details about the visualization and visual analytics as well as clinician/user front-ends.
- Finally, in section 6 an overall discussion on the feasibility and usefulness of this framework is presented.
- Section Appendix provides additional technical specifications that were not included in the main body of this document.

# 3 Requirements Identification and Analysis

The methodology employed for the design of the AR gaming framework for gait retraining follows a co-design approach, through a series of iterative steps, as shown in




The co-design approach to be followed for the design and implementation of the AR framework for gait retraining.

The steps that will guide the entire cycle of design and implementation of the AR framework for gait retraining include:

(1) Identification of a first set of user requirements from the initial analysis performed at proposal preparation stage (from DoW)
(2) Analysis of the functional and non-functional requirements and priorities as established in WP2 and described in deliverable D2.1 User Requirements Analysis Report.
(3) Definition of initial representative use cases and establishment of the initial system requirements based on steps 1 and 2
(4) SOA analysis of existing hardware and software tools and solutions relevant for the established initial system requirements
(5) Implementation of the initial prototype of the AR framework
(6) Iterative testing of the prototype with end users
(7) Analysis of end users feedback to refine and further detail the representative use cases
(8) Refining of the system requirements to account for the findings of the end user tests
(9) Deployment of the final synthesized AR framework and information visualization interface

The initial set of requirements as established at proposal preparation (from DoW) include:

- expanding & improving the currently limited opportunities for rehabilitation scenarios, by using gait retraining in an AR environment
- enhancing primitive spatial and temporal training scenarios, explored real-time visual and vibrotactile feedback to enable subjects to relearn their gait
- addressing staff and facility limitations as well as human factors,
- creating user friendly interfaces and integrating interactive environment,
- accurately implementing crucial stimuli (force sensing, visual information) together to have a real impact on the game task completion performance.

The user requirements and priorities, established in WP2 through interviews with experts and questionnaires and relevant for the implementation of the AR framework, as reported in D2.1 User Requirements Analysis report, include:

- Taking into account the needs of product usage stakeholders, including both business end (e.g. private clinicians) and customer end users (e.g. patients)
- Making sure that the framework does not add to the clinical workload, high-priority (score 0.774)
- Enable secure sharing of data between users (e.g. between patient and clinician), high-priority (score 0.792)
- Facilitate easy upload of associated data, high-priority (score 0.896)
- Support for free-text or unstructured text reports, high-priority (score 0.701)
- Support automatic anonymisation and pseudonymisation, high-priority (score 0.884)

Taking into account the user requirements as established in the first two steps, the initial analysis of the system requirements for gait retraining is performed in Section 4 of the current document, by obtaining the kinematics and kinetics of the users (patients) in two representative use cases, namely indoor and outdoor. These representative use cases are further analysed and their potential advantages and disadvantages discussed, in order to establish the first functional and non-functional requirements for the design and implementation of the AR framework and the information visualization interface.

The SOA analysis of hardware and software tools is performed in this document, based on the initial representative use cases (indoor and outdoor) and corresponding initial system requirements, resulting in the establishment of the initial design of the AR framework for gait retraining. The co-design process will allow for further refinements of both use cases and system requirements through tests with the end users (patients and clinicians), which will be reported along with the corresponding prototype release reports (D7.2, D7.3 and D7.4).

# 4 Gait Retraining

This section presents the gait retraining system of the OACTIVE project. The aim of this system is to reduce the Knee Adduction Moment (KAM) [1], [2] or other related indicators in order to improve patients' comfort and delay the progression of OA by adapting the gait habits of the users. Biofeedback assisted rehabilitation and intervention technologies have the potential to modify clinically relevant biomechanics. To perform this type of intervention one must obtain the kinematics and kinetics of user using either indoor or outdoor solutions. The indoor approach is more reliable and accurate in comparison to the outdoor solution, since we can use state-of-the-art measurement equipment, such as marker-based motion capture systems and ground reaction plates, that can be calibrated for the particular task. On the other hand, this approach may be impractical as it would take many sessions of training to alter the habit of the user and it would be preferable if we can perform this type of intervention out of the lab. Acquisition of the kinematics and kinetics for the analysis in an outdoor environment requires wearable solutions, such as IMUs and ground reaction smart shoes. In order to fully benefit of the advantages of each approach, we can use the indoor approach to validate the accuracy and performance of the outdoor solution.

The acquisition of the kinematics and kinetics, both indoor and outdoor, is the first step of the gait retraining module. The raw data must be filtered and refined in order to remove any undesirable artefacts that can affect the computational layer [3]. Additional steps must be performed in the case of the outdoor solution, where the extraction of the orientation form the IMUs is proved to be a challenging task due to the accumulation of drift errors [4]. The communication and synchronization of the devices pose a serious challenge both at the hardware and software level. Wireless communication solutions will be preferred as this will enhance the comfort of the user, but even more importantly the sensory data must be transferred for processing by the computation layer in order to provide real time feedback. Proper synchronization of the different devices is of great importance since the processing phase is very sensitive to this type of artifacts.

The next phase is the real time processing of the sensory data and the extraction of the metrics that would be used by the personalized intervention system. The essential element of this system is the Inverse Kinematics (IK) module, which determines the model configuration that bests fits the experimentally measured kinematics. IK module solves a non-linear optimization at each step of the analysis that minimizes some objective criterion. This phase should be executed in real time [5] to facilitate proper feedback response of the OACTIVE gait intervention module [6]. A secondary objective is the performance of an inverse dynamics analysis for the calculation of the joint moments that are important indicators of the knee pain and disease degeneration [7]. Optionally, one could move a step further by computing the muscle and joint reaction forces.

The information obtained from the real time simulation module will be used for comparison with the desired patient specific gait profile established by the DSS. The differences will be encoded and transmitted to the user in an intuitive manner through the feedback devices, using the AR and non-AR logic. In the indoor framework one can use simple, but effective solutions that would be based on simple screen projections. On the other hand, more advanced AR approaches would be required for the outdoor solution.

In the following subsections, we will present an overview of the hardware devise and software tools. Next, we will present the concept and design of the outdoor and indoor solutions.

## 4.1 Hardware Devices

### 4.1.1 Inertial Measurement Units

#### *Xsens MTw Awinda IMU System (Xsens Technologies BV, Enschede, NL)*

The MTw Awinda [8] is the second generation wireless inertial-magnetic motion tracker by Xsens. The MTw enables real-time 3D kinematic applications with multiple motion trackers by providing highly accurate orientation through an unobtrusive setup. The MTw is designed to be robust, easy and comfortable in usage, with easy placement on the body based on flexible hook and loop straps.

The MTw is a miniature IMMU (Inertial-Magnetic Measurement Unit) with a package size of 47 mm × 30 mm × 13 mm and a weight of 16 g. To sense the motion, the MTw contains inertial sensor components, namely a 3D rate gyroscope and a 3D accelerometer. In addition, it comprises a 3D magnetometer, a barometer, and a thermometer. The output of the SDI (Strap-Down Integration), along with the calibrated magnetometer and barometer data, is transmitted wirelessly using the Awinda Protocol to the Awinda Master. The data of the thermometer is used to compensate for the temperature dependency of the other sensing elements.

The Awinda Master serves as the interface between the Awinda host (typically a PC running Xsens-based software), and one or more MTw's. The Awinda Master ensures that the data from each MTw is synchronized to within 10 μs. Up to 20 MTw's can be wirelessly connected to a single Awinda Master. There are two different types of Awinda Master possible with the MTw system: the Awinda Station and the Awinda Dongle, which are both available as part of the MTw Awinda Development Kit.

Awinda Station: The Awinda Station is 148 mm × 104 mm × 31.9 mm in size. It includes the external antenna and 6 MTw docking slots. These slots are used for charging the MTws and firmware updates. Additionally, the Awinda Station has 4 BNC (Bayonet Neill–Concelman) hardware connections for TTL (transistor-transistor logic) time-synchronization with third party devices. The range of the wireless link using the Awinda Station is typically about 50 m in line of sight, guaranteeing complete freedom of movement and recording.

Awinda Dongle: The Awinda Dongle is a small USB device, measuring only 45 mm × 20.4 mm × 10.6 mm with USB connector, and 33 mm × 20.4 mm × 10.6 mm without the USB connector. The dongle has the same wireless communication possibilities as the Awinda Station. However, it does not have a range extender, which reduces the range to 10 m. To maximize portability, the Awinda Dongle is not equipped with hardware interfaces for charging MTw's or BNC ports for third party synchronization.

A detailed list of the technical specifications is given in the Appendix in Table 2.


Figure 2. The Xsens MTw Awinda hardware: a) MTw motion tracker; b) Awinda Dongle; c) Awinda Station; d) MTw body strap.

The Awinda Host receives the data from the Awinda Master through a USB connection. The host contains the Xsens Device API (XDA), of which XKF3-hm and the API are part of. XKF3-hm is a proprietary fusion filter, specifically developed to fit applications involving human movement. This filter provides accurate 3D orientation to the host application. The host application can be either MT Manager, the standard logging and visualization tool from Xsens, or an independently built program based on the Xsens software development kit (SDK).

#### *NGIMU (x-io Technologies, UK)*

The Next Generation IMU (NGIMU) is a compact IMU and data acquisition platform that combines on-board sensors and data processing algorithms with a broad range of communication interfaces to create a versatile platform well suited to both real-time and data-logging applications.

On-board sensors include a triple-axis gyroscope, accelerometer, and magnetometer, as well as a barometric pressure sensor and humidity sensor. An on-board AHRS (Attitude and Heading Reference Systems) sensor-fusion algorithm combines inertial and magnetic measurements to provide a drift-free measurement of orientation relative to the Earth. Each device is individually calibrated using robotic equipment to achieve the specified accuracy. Additional, external sensors, such as force or bend sensors, can be connected to the 8-channel analogue input interface. Serial data sources, such as GPS modules, can be connected to the auxiliary serial interface.

Real-time communication is achieved via USB, Wi-Fi, or serial/RS-232. Data may also be logged to an on-board micro SD card. The NGIMU uses the popular OSC (Open Sound Control) communication protocol and so is immediately compatible with many software applications and straight forward to integrate with custom applications with libraries available for most programming languages. The use of this protocol and the range of communication interfaces make the NGIMU compatible with just about any platform, from an Arduino to an iPhone.

A detailed list of the technical specifications is given in the Appendix in Table 3.

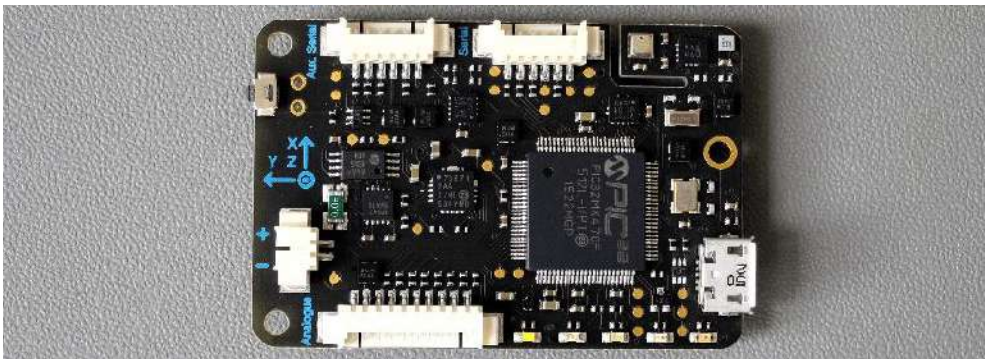


Figure 3. x-io Technologies' Next Generation IMU (NGIMU)

### 4.1.2 Ground Reaction Plates

#### *Multicomponent Force Plate Type 9281E (Kistler, Winterthur, Switzerland)*

The multicomponent force plate Type 9281E consists of a 600x400 mm aluminum sandwich top plate of rigid, lightweight construction and four built-in piezoelectric 3-component force sensors.

Thanks to the special properties of the piezoelectric sensors, the plate is highly sensitive and can simultaneously measure very dynamic phenomena involved in a wide spectrum of measuring tasks and application sectors. Despite the very generous measuring range of –10 ... 20 kN, it offers excellent accuracy and linearity, and even under a large preload allows precise measurement of minute forces. In all these situations the plate can be mounted in any position without affecting the measurement result in any way.

A detailed list of the technical specifications is given in the Appendix in Table 4.


Figure 4. Kistler's Multicomponent force plate Type 9281E force plate

### *AccuGait Optimized (AMTI, Watertown, MA)*

AMTI's AccuGait Optimized multi-axis force platform is a portable solution for quantifying human gait and balance. The system features multi-component measurement of forces and moments, while its design is accurate, economical, and easy to use with AMTI's NetForce/BioAnalysis software. The plug & play USB interface automatically synchronizes with up to 12 other AMTI USB acquisition products and eliminates external power supplies. Moreover, a one-piece sensor element provides high overload protection on all axes.

AccuGait Optimized attains high levels of accuracy for measuring Center of Pressure, forces and moments, as well as enormous reduction in crosstalk due to AMTI's unique precision grid calibration technology after taking 1275 measurements in a grid pattern and using the points for calibration.

A detailed list of the technical specifications is given in the Appendix in Table 5.

Figure 5 AMTI's AccuGait Optimized™ force plate.

### *In-shoe Pressure Measuring Systems*

In-shoe systems provide detailed information about what is actually occurring inside the shoe. It is the only way to analyze the interaction between the foot and the shoe. Evaluating plantar pressure through the use of an in-shoe system helps provide a better understanding of foot function, offers a more complete gait analysis and can help optimize orthotics used to treat pathologies.

### *F-Scan (Tekscan, Inc. South Boston, MA)*

The F-Scan™ in-shoe pressure measurement and analysis system that uses flexible, thin, trimmable sensors placed inside the shoe to capture timing and pressure information for foot function and gait analysis during a clinical test or research trial. The F-Scan system is suitable for profiling anatomical locations on the plantar surface, offering high spatial resolutions. Wireless and datalogger system options provide maximum flexibility for performing field tests and collecting real world, in-shoe data. The F-Scan system is available in different connection types depending on different needs:

F-Scan Base (Tethered): Wires connect the sensor and scanning electronics on the subject to the computer via USB port. The subject can be a distance of up to 30.5 meters (100 ft). Dynamic events are captured with high scan rates up to 750 Hz.

F-Scan Wireless: Data is transmitted directly from the subject to the computer. The subject can be up to 100 meters (328 ft) away and data can be recorded and displayed on the computer in real time. Scanning rates of up to 100 Hz are available with wireless connectivity.

F-Scan Datalogger: Collects and stores sensor data in its internal memory for upload to a computer at a later time, making it ideal for use when a recording needs to be made over an extended period of time. Scan rates of 750 Hz can be achieved.

F-Scan Wireless & Datalogger: With both options available, there is complete flexibility.

A detailed list of the technical specifications is given in the Appendix in Table 6.

Figure 6. Tekscan's F-Scan™ in-shoe pressure measurement and analysis system

### *The pedar® system (novel.de, Munich, GE)*

The pedar® system is an accurate and reliable pressure distribution measuring system for monitoring local loads between the foot and the shoe. It connects to highly conforming, elastic sensor insoles that cover the entire plantar surface of the foot, or to sensor pads for the dorsal, medial or lateral areas of the foot.

The pedar® can be tethered to a PC via a fiber optic/USB cable, or it can function in a mobile capacity with its built-in Bluetooth wireless telemetry system in a wide range. The dynamic pressure data can be viewed online. As another alternative, the pedar® has a SD card storage allowing data to be collected anywhere and later downloaded to the computer. Moreover, the pedar® system allows multiple synchronization options to use with EMG and video systems for gait analysis.

The pedar® can also be used for long-term monitoring. For that application novel has developed the pedoport software which allows long term monitoring of force or pressure over many hours and an efficient analysis for instance of overloading a certain force level. The pedar® biofeedback unit gives a real-time feedback signal if a given force or pressure threshold is exceeded.

A detailed list of the technical specifications is given in the Appendix in Table 7


Figure 7. The pedar® in-shoe pressure measurement and analysis system

### 4.1.3 Force-Sensing Treadmills

*Fully Instrumented Treadmill (FIT) (Bertec, Columbus, Ohio)*

Bertec's instrumented dual belt treadmills have been specifically designed for dynamic analysis of human locomotion. Through the use of strain gauge technology, innovative design, and quality manufacturing, Bertec's instrumented treadmills are well suited for locomotion applications in limited laboratory spaces. Each treadmill consists of a number of strain gauged load transducers and a built-in digital pre-amplifier for signal conditioning.

Each half of Bertec's dual belt treadmill incorporates an independent force plate measuring six load components – the three orthogonal components of the resultant force and the three components of the resultant moment in the same orthogonal coordinate system. The point of application of the force and the couple acting can be readily calculated from the measured force and moment components independently for each half of the treadmill.

Bertec treadmills use a state-of-the-art 16-bit digital technology for signal acquisition and conditioning. This technology makes the use of calibration matrices obsolete, since each treadmill half comes with the calibration matrix digitally stored on it. External amplifiers available for use with the treadmills provide the user with three signal output alternatives: digital, analog, or dual digital/analog outputs. The digital signal output can be directly plugged into the standard USB port of a personal computer without the requirement of an additional PC card for analog-to-digital conversion (ADC). This plug-and-play technology allows a simpler installation procedure in a minimum amount of time. The analog signal output can be fed into an ADC board so that data can be collected using conventional techniques. Depending on the application, signal amplification can be performed for analog output using external amplifiers. External amplifiers are either fixed or adjustable gain (four and seven adjustable gain models available). These amplifiers enable the user to establish a trade-off between the measurement range and the resolution of the treadmills.

Bertec's dual belt treadmills can easily be incorporated with the commercially available motion analysis systems to be used in a fully equipped locomotion laboratory.

Optional accessories for the treadmill are available as add-on features. These accessories include an incline feature, which can be used to tilt the treadmill up to 15° and a safety harness attachment.

A detailed list of the technical specifications is given in the Appendix in Table 8

Figure 8. Bertec's Fully Instrumented treadmill

### *AMTI Force-Sensing Tandem Treadmill (AMTI, Watertown, MA)*

AMTI's force-sensing treadmill uses an innovative tandem belt design that allows subjects to maintain a normal gait and eliminates many issues inherent to side-by-side, split-belt treadmills. With an AMTI tandem treadmill, subjects can walk naturally with no need to maintain their positions medial-laterally or straddle the belt split that runs down the center of the treadmill. Heel strike occurs on the front belt and the foot naturally translates to the rear belt for toe off as the subject walks. With only a 1 mm clearance between the two belts, they function as one continuous belt while preventing the data problems that occur during the double support phase of walking.

A six-axis AMTI force plate is located under each belt to record the GRF (Fx, Fy, Fz) and moments (Mx, My, MZ) generated by the subject. The force plates are an integral part of the treadmill design and each force plate entirely supports its own treadmill/drive motor assembly. High performance digital motor controllers and included software provide users with an intuitive interface for control of treadmill inclination, belt travel direction and belt speed up to 20 km/h. The extensive capabilities of the Tandem Treadmill make it an ideal method for studying both walking and running under level, uphill and downhill conditions.

A detailed list of the technical specifications is given in the Appendix in Table 9


Figure 9. AMTI's Force-Sensing Tandem Treadmill

#### 4.1.4 EMG Measuring System

*EMG Bluetooth measuring system (zebris Medical GmbH, Isny im Allgäu, GE)*

The zebris EMG-8 Bluetooth measuring system records muscle action potentials by means of bipolar skin surface electrodes. The system is suitable for measuring up to eight muscle groups simultaneously thus enabling dysfunctional muscle activation to be identified.

The data are transmitted to the PC wirelessly for each Bluetooth interface. An internal buffer memory bridges measurement times outside the reception range. The measurement results are displayed during the measuring programs in real-time on the PC and can be analysed. The measuring electronics is housed in an adapter that can be carried comfortably on the body, and the EMG electrode cables are fitted with active differential preamplifiers that eliminate interference voltages and cable/movement artifacts to a large extent.

A detailed list of the technical specifications is given in the Appendix in Table 10

Figure 10. The zebris EMG measuring system

Special cable with patient insulation for connection to a USB interface

*Shimmer3 EMG Unit*

The Shimmer3 EMG unit is a highly configurable sensor that measures and records the electrical activity associated with muscle contractions, assesses nerve conduction, muscle response in injured tissue, activation level, or can be used to analyse and measure the biomechanics of human movement. The Shimmer3 EMG sensor is non-invasive (Surface) EMG and therefore is a representation of the activity of the whole muscle. It's an efficient wireless solution for access to a host of muscle, gait, and posture data analysis.

The unit features software-configurable right-leg drive for common-mode interference rejection, software-configurable amplifier gain, software-configurable data rate, respiration demodulation capability on-chip, lead-off detection capability on-chip, test-signal on-chip for validation purposes, EEPROM storage device that enables expansion board detection and identification, as well as 2032 bytes of data storage available to user. It has two channels for recording EMG data, which can be also measured simultaneously with 10DOF kinematic data. Moreover, the EMG Unit contains ECG functionality as standard. However, EMG and ECG data cannot be measured simultaneously from a single unit.

A detailed list of the technical specifications is given in the Appendix in Table 11


Figure 11. Shimmer3 EMG Unit

### 4.1.5 Vibrotactile Feedback Devices

*C-2 Tactor (Engineering Acoustics, Inc., Casselberry, FL)*

The C-2 Tactor is a miniature vibrotactile transducer that has been optimized to create a strong, localized sensation on the body. Using a body-referenced arrangement of Tactors activated individually, sequentially or in groups, C-2 Tactors can provide intuitive "tactile" instruction to a user.

Figure 12. Engineering Acoustics' C-2 Tactor vibrotactile transducer.

The C-2 Tactor incorporates a moving "contactor" that is lightly preloaded against the skin. When an electrical signal is applied, the "contactor" oscillates perpendicular to the skin, while the surrounding skin area is "shielded" with a passive housing. Thus, unlike most vibrational transducers (such as common eccentric mass motors that simply shake the entire device), the C-2 provides a strong, point-like sensation that is easily felt and localized.

For optimum vibrotactile efficiency, the C-2 is designed with a primary resonance in the 200-300 Hz range that coincides with peak sensitivity of the Pacinian corpuscle, the skin's mechanoreceptors that sense vibration. The C-2's high force and displacement level allow the vibration to be easily felt at all locations on the body, even through layers of clothing.

A detailed list of the technical specifications is given in the Appendix in Table 12

### 4.1.6 Motion Capture Cameras

*Vicon Vantage V16 (Vicon, Oxford, UK)*

Vicon's Vantage motion-capture camera exploits powerful processing algorithms and electronics, combined top-level tracking and data fidelity that allows it to achieve high resolution and speed levels. The Vantage features onboard sensors, LEDs and a digital display that are combined to provide an up-to-the-minute system status and feedback on the fly.

Vantage can be controlled with Vicon's Control smartphone application to change camera settings, calibrate the system, and start or stop capture, thus saving time during camera set-up and capture.

A detailed list of the technical specifications is given in the Appendix in Table 13


Figure 13. Vicon's Vantage V16 motion-capture camera.

*Kestrel 4200 (Motion Analysis Corp., Santa Rosa, CA)*

The Kestrel 4200 is a compact, wide format camera capable of 200 fps with a sensor resolution of 2080 x 2048 pixels (4.2 million). The Kestrel Digital Cameras assures reliable and accurate data acquisition by exploiting digital technology that produces no degradation of the signal over distance and less noise, and requires no resampling of data on another piece of electronics. The Kestrel Digital Camera signal is sent directly to the tracking computer via an Ethernet connection, while the signal processing is embedded in the camera. This streamlined system of motion capture from camera to computer means less hardware and easier maintenance.

Cortex is Motion Analysis' software for handling all phases of motion capture within a single program – initial setup, calibration, tracking and post processing.

A detailed list of the technical specifications is given in the Appendix in Table 14


Figure 14. Motion Analysis' Kestrel 4200 motion-capture camera.

#### 4.1.7 Video Projectors

*Optoma HD144X (Optoma Corporation, New Taipei City, Taiwan)*

Optoma's HD144X projector provides reliable performance suitable for any content and environment. The projector is capable of reproducing the Rec.709 colour gamut, the international HDTV standard, in

Full HD 1080p resolution providing sharp and detailed images from HD content without downscaling or compression. It uses dynamic black technology that gives more depth to the image by smoothly adjusting the lamp output, based on the brightness information of each frame.

Optoma's HD144X features an integrated speaker and two HDMI inputs enabling a convenient and easy setup with a laptop, PC, Bluray player, media streamer or games console. Also, it can connect to smartphones or tablets with a single cable using MHL. The HD144X projector can display true 3D content from almost any 3D source, including 3D Blu-ray players, 3D broadcasting and the latest generation games consoles, and can accept high definition sources at 24 fps.

A detailed list of the technical specifications is given in the Appendix in Table 15

Figure 15. Optoma HD144X projector

### *Epson EH-TW5650 (Epson, Suwa, Nagano Prefecture, Japan)*

Epson's EH-TW5650 is an easy set-up, Full HD, projector with lens shift and 60,000:1 contrast ratio, providing equally high White and Colour Light Output of 2,500 lumens. With this projector images can reach up to 300 inches (762cm). The projector incorporates a range of high-tech features such as, frame interpolation technology that inserts new frames between existing ones to suppress blurring, advanced image processing that provide sharper, crisper images with five preset modes available, and enhanced depth and clarity and more detailed gradation between the light and dark areas.

The EH-TW5650 features a built-in 10W speaker, discarding the need to connect the projector to an amplifier or separate speaker. The long-lasting lamp light source (7,500 hours lamp life) makes the EH-TW5650 a long-term, hassle-free and affordable solution. The 1.6x zoom along with horizontal keystone correction function and lens shift, provides a wide range of placement options even in a limited space. The projector can be connected wirelessly with Miracast compatible smart devices, or a streaming device to the HDMI terminal to project wirelessly using an application on a smartphone or tablet. It is possible to project directly from a smart device with the iProjection app and built-in Wi-Fi.

A detailed list of the technical specifications is given in the Appendix in Table 16


Figure 16. Epson EH-TW5650 projector

### 4.1.8 Rehabilitation Devices

*Rehawalk® (zebris Medical GmbH, Isny im Allgäu, GE)*

The treadmill-assisted zebris Rehawalk® system is designed for the analysis and treatment of gait disorders in neurological, orthopedic and geriatric rehabilitation. Therapy with Rehawalk® assists patients in reaching a safe and effective gait through functional and cognitive challenges that can be individually adapted to the patient's capability.

In addition to a treadmill, Rehawalk® includes a unit for adaptive visual cueing through the projection of gait patterns on the treading surface. During training the steps are projected onto the treadmill belt in the shape of the actual footprints, or alternatively as rectangles or as ovals. Throughout the gait training the patient is instructed to position his or her feet as accurately as possible within the projected surface area.

Virtual feedback training happens simultaneously with the help of a large monitor mounted in front of the treadmill. The patient moves in a virtual walking environment, and while observing the footprints performs various tasks which require a continual variation of walking and balancing. Physical and cognitive abilities are simultaneously demanded during dual-task-training. The patient solves simple perceptual and memory tasks as well as arithmetic problems while walking. Thus, reaction time and attentiveness are improved while simultaneously supporting automated walking.

Due to the high number of step repetitions, an automation of motion sequences is achieved providing complete protection against falling and additional weight unloading at the same time.

The system automatically documents the course of treatment through the easy-to-operate software and in-depth evaluation reports. For recording kinematic parameters and video documentation, an integrated lighting and camera unit is optionally available.

A detailed list of the technical specifications is given in the Appendix in Table 17


Figure 17. Zebris' Rehawalk® gait analysis and gait training system

### 4.2 Software Tools

A physics engine is a software tool used to simulate physical phenomena. They can detect collisions of objects, simulate rigid bodies under the influence of forces, simulation of soft body dynamics or fluid dynamics etc. Generally, there exist two types of physics engines: Real – time and High – precision. Real – time physic engines are generally used in video games and they perform simplified calculations with decreased accuracy to limit the computational time, whereas high precision physic engines demand high computational power in order to make precise calculations.

In the following we present several game engines that provide high accuracy simulations like SOFA and real time simulations like Bullet and Havok. The latter two are more commonly used for video games. We also present physic engines that offer high accuracy and are specifically designed for biomechanical applications.

#### 4.2.1 Bullet

Bullet Physics is a professional open source collision detection, rigid body and soft body dynamics library written in C++. It is primarily designed for use in games, visual effects and robotic simulation. It is portable and so it can be used in multiple systems as Microsoft Windows, OS X, Linux, iOS, Android, PlayStation 3, Xbox 360 and Wii. The library is free for commercial use under the ZLib license. Several of the main features it provides are:

- Discrete and continuous collision detection including ray and convex sweep test. Concave and convex meshes can define collision shapes.
- Rigid bodies can have maximal coordinate 6 – degree of freedom and can be connected by constraints as well as generalized coordinate multi – bodies connected by mobilizers using the articulated body algorithm.
- Fast and stable rigid body dynamics constraint solver.
- Soft body dynamics for deformable volumes.
- Blender integration, Maya Dynamica plugin. (Bullet Physics SDK Manual)

#### 4.2.2 SOFA

Simulation Open Framework Architecture (SOFA) is an open-source C++ library primarily targeted at interactive computational medical simulation. It is written in C++ and Python and operates on Microsoft Windows, Linux and OS X. SOFA introduces the concept of scenegraph-based multi-model representation to easily build simulations composed of an arbitrary number of objects. A hierarchical data structure is used to describe the list of simulated objects and algorithms used in simulation. The objects can be decomposed into collections of independent entities that can describe one feature of the model such as state vectors, mass, forces etc. Thus, changing the characteristics of one component leaves the other components unchanged. Some features of the library are:

- Interaction with VR / simulation devices: Geomagic®, ARTTrack™, Novint® Falcon™, etc.
- Parallelization methods like GPU computing using CUDA API
- Python Scripting

### 4.2.3 AnyBody

AnyBody is a commercial musculoskeletal modelling software used for biomechanical simulations. It analyses the reactions within the human body or between the body and objects of the external environment. Although any musculoskeletal system can be model e.g. a bird, it comes with a full body model available for the user to adapt it on his needs. It is focused mainly on inverse simulation. Several features of this software are:

- Musculoskeletal analysis of daily activities
- Self – contained robust system
- Inverse dynamics
- Force – dependent kinematics
- Motion prediction
- Interface to C3D, BVH and FEA

### 4.2.4 OpenSim

OpenSim is an open source software for modelling, simulating and analysing the neuromusculoskeletal system. It is written in C++ and the GUI is written in Java. It includes low – level computational tools utilized by the application. It runs on Microsoft Windows, OS X and Linux. The user can employ the models provided by the OpenSim community, modify them to match his needs or he can develop his own model. Also, OpenSim provides the necessary SDK so the user can develop his own model with C++. Several features of OpenSim are:

- Performing IK analyses to calculate joint angles from marker positions.
- Performing ID analyses to calculate joint moments from joint angles and external forces.
- Generating forward dynamics simulations of movement.
- Analysing dynamic simulations.
- Plotting of the results.

### 4.2.5 LifeMOD

LifeMOD is a commercial virtual human modelling and simulation software developed by LifeModeler. It is mainly focused on inverse simulation. LifeMOD can be integrated into corporate computer-aided engineering (CAE) workflows, it can import geometries from computer-aided design (CAD) systems and easily imports engineering-formatted data from MRI and CT scans. Some of its main features include:

- Inverse and forward dynamics.
- Easy to use, since with several parameters such as age, height, weight or gender it automatically from an anthropomorphic database creates the proper bones, muscles and joints for a subject.
- Life-like motion with 3D motion-capture import.

### 4.2.6 Havok

Havok Physics is designed mainly for video games and is concentrated on real – time collisions and rigid body dynamics. It supports many platforms like Microsoft Windows, Linux, Android, macOS, iOS, Xbox 360, PlayStation 4, Wii, Switch etc. It supports a wide variety of useful game-ready constraint types including ragdolls and it is highly robust, for continuous collision detection for environments, characters and vehicles.

### 4.2.7 Summary

The following table compares several features of the toolkits presented above.

| | Real time/ High accuracy | Usage | Licence | Extensibility |
|---|---|---|---|---|
| Bullet | Real time | Video Games | Open Source | Yes |
| SOFA | High Accuracy | Medical Simulations | Open Source | Yes |
| Anybody | High Accuracy | Biomechanics | Commercial | No |
| OpenSim | High Accuracy | Biomechanics | Open Source | Yes |
| LifeModeler | High Accuracy | Biomechanics | Commercial | No |
| Havok | Real time | Video Games | Proprietary | Yes |

From the summary table, we see that the most specific application for our purpose is OpenSim. It is designed for Biomechanical simulations, it is open source and easily extendable. Thus, we can integrate our own custom built models that are designed specifically for the patient.

## 4.3 AR Hardware Devices

### 4.3.1 Desktops

#### *Apple iMac (2017)*

The latest version of Apple's iMac is packed with all-new processors, the latest graphics technologies, innovative storage, and higher-bandwidth connectivity. It comes in two models; the 21.5-inch and 27-inch model.

The iMac is equipped with seventh-generation Intel Core i5 and i7 processors, taking the 27-inch model up to 4.2GHz, and the 21.5-inch model up to 3.6GHz, while Turbo Boost can give even more power when using processor-intensive applications.

The iMac features Radeon Pro 500 series graphics. The 27-inch iMac with Retina 5K display is loaded with up to 8GB of dedicated VRAM, and the 21.5-inch iMac with Retina 4K display with up to 4GB.

For storage iMac features the Fusion Drive which is both speedy and spacious. Fusion Drive available in standard configurations of both the 27-inch and 21.5-inch Retina models. The apps and files used the most are automatically stored on fast flash storage, while everything else moves to a high-capacity hard drive.

The Retina display uses P3 colour that shifts away from standard white LEDs to advanced red-green phosphor LEDs. So, all three colours - red, green, and blue - are more equally represented and show off real-world colour with more balance and precision.

Two Thunderbolt 3 (USB-C) ports come standard on all iMac models, each delivering up to 40Gb/s data transfer for external drives and cameras and twice the bandwidth for video and display connectivity. Thunderbolt 3 lets the addition of one 5K display, or, as another option, two 4K displays can be connected instead. Four USB 3 ports give plenty of options for connecting peripherals. Lastly, iMac uses three-stream Wi‑Fi and Bluetooth 4.2 wireless technology.

A detailed list of the technical specifications is given in the Appendix in Table 18

Figure 18. Apple's iMac

### *Dell XPS Tower Special Edition*

The XPS Tower Special Edition is a high-performance, VR-ready desktop featuring big power with the latest Intel® processors, advanced graphics and an easy-open, brushed aluminum chassis for simple expandability.

The Intel® i5 or i7 Core™ processors offer more power potential with a BIOS option for overclocking. Opt for up to NVIDIA's GeForce® GTX™ 1080, the XPS Tower Special Edition can provide elite virtual reality, HD and ultra-resolution 4K displays. With memory up to 32GB DDR4 SDRAM 2400MHz and a cached hard drive that uses Intel® Smart Response Technology, the tower can provide the large storage capacity of a hard drive and the responsiveness of a solid-state drive. The tower can support up to 225W full size graphics cards and up to four storage devices with capacity for three 3.5" HDD bays or 2.5" NB drives plus one internal optical drive. Lastly, there are 11 USB ports, including one USB Type-C port and four front USB ports.

A cooling system based on Alienware-inspired thermal design (thermally controlled fans) ensures that the desktop stays cool under intensive loads. The 3-heat-pipe system, available with optional k-skus, moves heat efficiently from the CPU without exceeding Dell's rigorous acoustic limits.

A detailed list of the technical specifications is given in the Appendix in Table 19


Figure 19 Dell's XPS Tower Special Edition

## 4.3.2 Smartphones

### *Samsung Galaxy S9/S9 Plus*

The Samsung Galaxy S9 and Samsung Galaxy S9+ are Android smartphones produced by Samsung Electronics as part of the Samsung Galaxy S series. They both feature 1440p Super AMOLED displays, with an 18.5:9 aspect ratio. The S9 has a 5.8-inch panel, while the S9+ uses a larger 6.2-inch panel.

The S9 and S9+ both come with a Samsung Exynos 9810 SoC (System on Chip). The S9 comes with 4 GB of RAM; the S9+ comes with 6 GB of RAM. Both devices come with storage options of 64, 128 and 256 GB, and feature the ability to use a microSD card to expand the storage to a maximum of 512 GB.

The battery capacities are 3000 mAh for the S9, and 3500 mAh for the S9+. The S9 and S9+ have stereo speakers tuned by AKG Acoustics and the phones also have Dolby Atmos surround sound support. Furthermore, the S9 and S9+ retain the 3.5mm headphone jack. The fingerprint sensor has a centralized location just below the camera. Face recognition and iris scanning have been merged into one and called Intelligent Scan.

The S9+ has a dual-lens camera setup on the back, while the S9 only has a single camera on the back. Both phones have a Dual Aperture rear camera which can switch between f/1.5 and f/2.4, depending on lighting conditions. The phones can shoot 4K at 60 frames per second (limited to 5 min), 1080p at 240 frames per second and 960 frames per second "Super Slo-Motion " video at 720p.

The S9 and S9+ ships with the Android 8.0 "Oreo" mobile operating system with Samsung's Samsung Experience 9.0 skin on top of it.

A detailed list of the technical specifications is given in the Appendix in Table 20


Figure 20. Samsung's Galaxy S9 and S9+

### *iPhone XS / iPhone XS Max*

iPhone XS and iPhone XS Max are smartphones designed, developed and marketed by Apple Inc. The XS features the A12 Bionic chip built with a 7 nanometer processor. It also features a 5.85-inch (149 mm) OLED display and contains dual 12-megapixel rear cameras and one 7-megapixel front-facing camera. The XS Max features the same hardware and cameras, but has a larger 6.46-inch (164 mm) OLED display and battery (3,174mAh).

The XS and XS Max are rated IP68 for dust and water resistance under IEC standard 60529, with Apple specifying a maximum depth of 2 meters and up to 30 minutes of submersion in water. Lastly, both iPhone XS devices have optical zoom and support dual SIMs through a Nano-SIM and an eSIM.

A detailed list of the technical specifications is given in the Appendix in Table 21


Figure 21. Apple's iPhone XS and XS Max

### 4.3.3 Tablets

*iPad Pro*

The iPad Pro family is a line of iPad tablet computers designed, developed, and marketed by Apple Inc., that runs the iOS mobile operating system. It is currently available in two screen sizes, 11-inch (28 cm) and 12.9-inch (33 cm), each with four options for internal storage capacities: 64, 256, 512 GB or 1 TB.

The redesigned 2018 models feature new edge-to-edge Liquid Retina displays, Face ID, improved 12MP cameras, USB-C connectors, and Apple A12X Bionic processors.

iPad Pro is thinner than the thinnest laptop. It weighs barely a pound and has up to 10 hours of battery life.

A detailed list of the technical specifications is given in the Appendix in Table 22


Figure 22. Apple's iPad Pro

### *Samsung Galaxy Tab S3*

Samsung's Galaxy Tab S3 features a 9.7" 2,048 x 1,536 Super AMOLED display which supports HDR video. The Tab S3 has a Qualcomm Snapdragon 820 processor, 4GB of RAM, 32GB of on-board storage and a 6000mAh battery. It is also supplied with a Samsung Galaxy Note series S Pen. The Galaxy Tab S3 runs Android Nougat as default.

A detailed list of the technical specifications is given in the Appendix in Table 23

Figure 23. Samsung's Galaxy Tab S3

## 4.3.4 Augmented Reality Smartglasses

### *Microsoft HoloLens*

Microsoft HoloLens is a pair of mixed reality smartglasses developed and manufactured by Microsoft that is capable of projecting holograms (3D visualizations) in the environment of use.

The HoloLens features an inertial measurement unit (IMU) (which includes an accelerometer, gyroscope, and a magnetometer), four "environment understanding" sensors, an energy-efficient depth camera with a 120°×120° angle of view, a 2.4-megapixel photographic video camera, a four-microphone array, and an ambient light sensor. The integrated speakers do not obstruct external sounds, allowing the user to hear virtual sounds, along with the environment. The HoloLens generates binaural audio, which can simulate spatial effects; meaning the user, virtually, can perceive and locate a sound, as though it is coming from a virtual pinpoint or location.

In addition to an Intel Cherry Trail SoC containing the CPU and GPU, HoloLens features a custom-made Microsoft Holographic Processing Unit (HPU), a coprocessor manufactured specifically for the HoloLens by Microsoft. The HPU uses 28 custom DSPs from Tensilica to process and integrate data from the sensors, as well as handling tasks such as spatial mapping, gesture and gaze recognition, and voice and speech recognition.

HoloLens features IEEE 802.11ac Wi-Fi and Bluetooth 4.1 Low Energy (LE) wireless connectivity. The headset uses Bluetooth LE to pair with the included Clicker, a thumb-sized finger-operating input device that can be used for interface scrolling and selecting.

Microsoft Visual Studio can be used to develop applications (both 2D and 3D) for HoloLens. Applications can be tested using HoloLens emulator (included into Visual Studio 2015 IDE) or HoloLens Development Edition. Unity engine and Vuforia can be used to create 3D apps for HoloLens, but it's also possible for a developer to build their own engine using DirectX and Windows APIs.

A detailed list of the technical specifications is given in the Appendix in Table 24

Figure 24. Microsoft's Hololens smartglasses

### *Magic Leap One*

Magic Leap One is a mixed reality/augmented reality HMD developed by the tech startup Magic Leap. The Magic Leap One mixed reality system comprises of three hardware components. The Lightwear headset, the Lightpack computer and the Controller.

The headset is modeled on Steampunk sunglasses in two sizes. The goggles also have the option of custom temple, nose, forehead pads and the inclusion of prescription lenses into the goggles. To gather spatial data, the headset comes equipped with multiple integrated sensors and external cameras. This sensor suite detects objects, planes, and surfaces in the surrounding environment and allows their reconstruction. Like Microsoft HoloLens, the Magic Leap One has built-in speakers and built-in microphones, four of them in the headset.

Magic Leap uses Photonic Wafers, which are translucent cells that generate Lightfield signals. The Digital Lightfield Technology uses photonics to create lights of various depths and combines them with natural light to generate virtual objects. The lightfield/digital objects that the user created and placed in a physical environment will remain there until it is moved or removed by the user. The virtual objects are not only capable of just establishing their presence along with the real objects, but are able to interact with the surrounding physical world as well.

The computer that powers the headset comes in the form of a compact disc-shaped hip-pack. The device comes with a clip-on mechanism to attach to the belt or shoulder pad and is tethered to the headset. The Magic Leap Mixed Reality System has another computer situated in the goggle/headset that shares the workload of the Lightpack Computer. The secondary computer, which has limited computing power, has machine learning capabilities and is tasked to handle detection of the surrounding environment.

The third hardware component of the mixed reality system is the handheld controller used to navigate the menus and thoroughly participate in the mixed world created by Magic Leap One. Also, the controller can be tracked in space. The system accepts multiple input modes including eye tracking, head position, gestures, and voice command inputs.

Applications run on Lumin, the operating system, which is derived from Linux and Android Open Source Project (AOSP). The company's software development kit, called "creator," offers resources for people who want to build apps on the Unreal or Unity engines.

A detailed list of the technical specifications is given in the Appendix in Table 25

Figure 25. Magic Leap One

### *Moverio BT-300 Smart Glasses*

The Moverio BT-300 is a pair of mixed reality smartglasses developed by Epson. It features the Si-OLED technology that it used for the display. It spots a transparent display that projects images on an 80 inches floating screen 5 meters in front of your eyes. The display, when turned off, are totally invisible as it merges seamlessly to the glasses. There is also a 5 Megapixel camera located at the front of the glasses along with the motion and ambient light sensors.

The smart glasses are powered by Intel Axom 5 processor and runs on Android 5.1 Lollipop providing a popular platform for games and apps to be developed. Developers, however, would need to download an SDK from the products developer page.

The Moverio BT-300 is connected to an Android controller that has a trackpad and basic Android buttons through a wire. This provides a familiar interface to existing Android users.

A detailed list of the technical specifications is given in the Appendix in Table 26

Figure 26. Moverio BT-300

### *Meta 2 Development Kit*

The Meta 2 VR headset features a full 90-degree field of view and 2560 x 1440 high-dpi display. The see-through headset makes everything below the eyebrow-level transparent, allowing users to make eye contact with others. The headset itself is lightweight and designed to be as comfortable as possible. The Meta 2 also accommodates for people who wear glasses. Meta 2 is a tethered device which requires the horsepower of a computer to display everything it can. This version of the Meta is tethered to a computer via a 9-foot cable, either HDMI 1.4b or DisplayPort.

Developers can use the freely available SDK to build and share tools. The included Meta 2 SDK is built on top of Unity, which enables the creation of holographic apps. Also, its open nature makes it possible to integrate with a wide range of accessories.

A detailed list of the technical specifications is given in the Appendix in Table 27.

Figure 27. Meta 2

Below we compare the technical specification of the different AR smartglasses described above, that meet the functional requirements in terms of processing power required for the development of software applications and the flexibility provided to the user. From this analysis, we drove the conclusion that the Meta 2 is more suitable for game-like applications required by the OACTIVE project, since it provides the computational power of a PC, lacking, however, the flexibility required for the outdoor/mobile solution described in section 4.6. Thus, it is best fit for the immobile/indoor solution.

Table 1. Comparison Table of Augmented Reality Smartglasses

| | Microsoft HoloLens | Magic Leap One | Moverio BT-300 | Meta 2 |
|---|---|---|---|---|
| Connection | Wireless | Wireless | Wireless | Tethered |
| CPU | Intel 32-bit (1GHz) | NVIDIA® Parker SOC; 2 Denver 2.0 64-bit cores + 4 ARM Cortex A57 64-bit cores | Intel® Atom™ x5, 1.44GHz Quad Core | PC-dependent |
| Memory | 2 GB RAM | 8 GB RAM | 2 GB RAM | PC-dependent |
| Storage | 64 GB (flash memory) | 128 GB (actual available storage capacity 95GB) | Internal: 16 GB External: Micro SD (max.2GB), MicroSDHC (max. 32GB) | PC-dependent |
| Display | 2.3 megapixel | N/A | 921,600 pixels (1,280x 720 resolution) | 3.6 megapixel (2550x1440 resolution) |
| GPU | 1 GB HPU RAM | NVIDIA Pascal™, 256 CUDA cores | N/A | PC-dependent |

## 4.4 AR Software Tools

### 4.4.1 Game Engines

A game engine is a software suite designed to facilitate the production of computer games. Game engines are used by the developers to create games for game consoles, personal computers and growingly mobile devices. Their advantage is that they provide a flexible and reusable development toolkit with all the core functionality required to produce a game quickly and efficiently.

A common misconception is that a game engine only draws the graphics we see on the screen. In fact, a game engine is a collection of interacting software that together makes a single unit. An engine architecture is mainly composed by the following subsystems:

- Audio
- Input
- Physics
- Renderer
- Artificial Intelligence
- Core
- Scripting
- Networking

In the current section several commonly used game engines are briefly described:

#### *Unity 3D*

Unity 3D is a cross-platform game engine with a built-in IDE developed by Unity Technologies. It is used to create video games for web, desktop, game consoles and mobile devices. It is programmed in C/C++ and supports C#, UnityScript (JavaScript for Unity) and Boo. Also, .NET languages can be used with Unity if they can compile a compatible DLL file. Currently the Unity Editor is supported only on Windows and Mac. It can be used to develop games that can be deployed to more than 25 platforms with those of using VR technology also included, like Oculus Rift, Playstation VR, Gear VR, Google ARCore, Google Cardboard Android & iOS etc. Several of the features supported are:

- 2D and 3D development
- AI pathfinding tools
- Box2D and NVIDIA PhysX physics engines
- Real-time rendering engine

### Unreal Engine 4

Unreal Engine 4 is a complete suite of development tools made for anyone working with real-time technology. It supports a variety of platforms like Windows, macOS, Linux, iOS, Android, PlayStation 4, Nintendo Switch etc, as well as Virtual Reality applications like Oculus Rift, PlayStation VR, Samsung Gear VR etc. Due to the fact that Unreal Engine is written in C++ with complete C++ source code access, it offers high portability and can be customized and debugged to match the needs of the developer. It also permits scripting through UnrealScript. Some other of the features it includes:

- Blueprints: Create without Coding.
- Extensive Animation Toolset.
- Sequencer: State-of-the-Art Cinematics.
- Flexible Material Editor.
- Built for VR, AR and XR.
- Full Editor in VR Mode.

### CryEngine

CryEngine is a game engine designed by Crytek. It is written in C++, C# and Lua. The platforms it supports are iOS, Android, Windows, Linux, Oculus Rift, Playstation, Xbox, and Wii. It gives the full engine source code with all features with no royalties, no obligations, and no license fees in return. Several of the features supported by CryEngine are:

- Voxel – Based Global Illumination (SVOGI)
- Physically Based Rendering
- #D HDR Lens Flares
- Real – Time Local Reflections
- Realistic Vegetation
- Real – Time Dynamic Water Caustics
- Material Editor
- FBX Support

#### AppGameKit

AppGameKit is a game engine developed by The Game Creators Ltd. AppGameKit offers an easy to learn high level scripting language called AGK BASIC, but the user has also the option to program by using the build in C++ libraries. It supports platforms like iOS, Android, Windows Phone, Windows, Mac, Linux etc. One can deploy a mobile game on as many platforms with just a single codebase. With the AppGameKit VR add-on it permits full development control for SteamVR supported head mounted displays, touch devices and Leap Motion hand tracking. It also supports the development of AR applications and supports 3D graphics. Finally, the AppGameKit Mobile available on Google Store and Apple Store permits "code on the go", namely it gives the opportunity to code on AppGameKit then compile and run your projects directly on your mobile phone.

#### Godot

Godot is a free open source game engine distributed under the licence of MIT. It is written in C and C++ and the IDE runs in Windows, macOS, Linux, BSD and Haiku, aiming the development of games for PC, web and mobile. It supports scripting on GDScript a python like scripting languge, as well as Visual scripting, scripting using Python, Nim, D and other languages and finally supports C# using Mono and C++. It supports platforms like Windows, Mac, Linux, iOS, Android, iOS, BlackBerry, HTML5, PlayStation, Nintendo etc. Currently VR is supported, but AR is still on the development process.

### 4.4.2 Mobile Operating Systems

Nowadays smartphones provide much of the functionality of a personal computer, such as web browsing, using of applications, social networking, GPS usage etc. A mobile operating system is an operating system or a software platform on which other programs can run on mobile phones, smart watches and tablets. Although there exist a large variety of mobile OS the most popular among them in the market are Android OS and iOS. In the next, we briefly describe some of their features along with the tools used for developing applications.

#### Android

Android is a mobile operating system designed by Google Inc. It is a Unix – like operating system as the heart of the whole system is a Linux Kernel. Its architecture is composed of a stack of different layers of software. These are: the android applications, an operating system, the android run – time, the middleware, services and libraries. The components of each layer as well as each layer of the stack are tightly integrated and provide the necessary services to the layer just above it in order to achieve the optimal application development and performance. It is mainly written in C, C++ and Java and concerning its license it is considered a free and open – source software, but usually bundled with proprietary apps and drivers. It runs on Smartphones, tablets, computers, TVs, cars and wearable devices. Concerning the development of android applications, Google provides the Android Studio IDE. It runs of Windows, macOS and Linux. The Android Studio will automatically get the latest version of the Android SDK and it provides an SDK Manager in order to download the necessary packages to develop a specific application. Android Studio is enriched with an Android Emulator in order to test the developed application. On Windows, the development of Android applications can also be accomplished using Visual Studio. In order to do so the user must have set up the Xamarin software kit that permits the user to build cross platform applications. Users are utilizing a C#-shared codebase in order to develop.

#### *iOS*

iOS is a mobile operating system developed by Apple Inc. It is a Unix – like operating system as the iOS kernel is the XNU kernel of Darwin. It is written in C, C++, Objective – C and Swift. In contrast to Android, iOS is a closed source software and used on apple devices as iPhone, iPad, iPod Touch and Apple Watch. iOS has a layered architecture. From a top to down approach these layers are: Cocoa Touch, Media, Core Services and Core OS. Lower levels give basic services which all application relies on, whereas the higher ones give sophisticated graphics and interface related services.

Concerning the development of iOS applications, the user needs an Apple computer with macOS in order to install Xcode IDE. Xcode includes all the necessary features to design, develop, and debug an app. Xcode also contains the iOS SDK, which extends Xcode to include the tools, compilers, and frameworks you need specifically for iOS development. We must note here that iOS SDK is free to download for macOS users but not for Windows users. Also, the developer can make use of the Objective – C programming language, but nowadays he can also use the new Swift language which is designed to work with Apple's Cocoa and Cocoa Touch frameworks. One can not only develop an application entirely on Swift, but also, he can achieve co-existance of Swift code with Objective – C code in the same application.

### 4.4.3 AR toolkits

In this section we present several toolkits that are used in order to develop Augmented Reality applications.

### Wikitude

Wikitude SDK is a software toolkit that enables the development of Augmented Reality applications on mobile devices. It supports the development of iOS and Android applications and it also provides extensions to mobile app development platforms including Appcelerator Titanium, PhoneGap and Xamarin. It provides powerful features like:

- Object & Scene Recognition
- Image Recognition
- Instant Tracking
- Location – Based Services
- Multiple Image Target
- Extended Tracking
- Cloud Recognition
- 3D Augmentations etc.

In order to assist the development of AR application this software comes with the Wikitude Studio. It is not necessary for the user to have programming skills since the Studio is an easy drag and drop tool.

### ARKit

ARKit is an SDK for software developers to create augmented reality apps and games for iPhones and iPads. Several features are supported by ARKit are:

- Augmented reality framework for iOS 11
- Visual Inertial Odometry (VIO) tracks positions and movement
- Scene and horizontal plane detection
- Lighting estimation
- Works with third-party development tools
- Face Tracking for iPhone X.

At the current Apple has released the ARKit 2 version which has several new features, like: it is compatible to work with iOS 12, incorporates real-world objects into the users AR experiences, Shared AR experiences simultaneously like on multiplayer games and adds the ability to detect known 3D objects like sculptures, toys, or furniture.

### ARCore

ARCore is Google's platform for building augmented reality experiences. Using different APIs, ARCore enables your phone to sense its environment, understand the world and interact with information. Some of the APIs are available across Android and iOS to enable shared AR experiences.

ARCore uses three key capabilities to integrate virtual content with the real world as seen through your phone's camera:

- Motion tracking allows the phone to understand and track its position relative to the world.
- Environmental understanding allows the phone to detect the size and location of all type of surfaces: horizontal, vertical and angled surfaces like the ground, a coffee table or walls.
- Light estimation allows the phone to estimate the environment's current lighting conditions.

ARCore can work with different development environments as:

- Android Studio.
- Unity.
- Unreal.
- iOS

### Vuforia

**Vuforia** is an SDK for mobile devices that enables the creation of Augmented Reality applications. Vufora engine can be integrated to other development software tools like: Xcode, Android Studio, Visual Studio and Unity. Several of its features are:

- **Model Targets**: object recognition by shape using pre-existing 3D models.
- **Image Targets**: putting AR content of flat objects.
- **Mutli Targets**: for objects with flat surfaces and multiple sides, or that contain multiple images.
- **Cylinder Targets**: placing of AR content on objects with cylindrical and conical shapes.
- **Object Targets**: Object Targets are created by scanning an object. They are a good option for toys and other products with rich surface details and a consistent shape.
- **VuMarks**: identification and addition of content to series of objects.

Several new added features include:

- External Camera or usage of an independent camera beyond the camera equipped in phones and tablets.
- Support for ARCore 1.4.
- Increased ability to detect small targets.
- Support for DragonBoard™ 410c.

#### 4.4.4 Relevant Applications

In this section we present several applications currently available either on Google Store or Apple Store that aim to exercise the lower limb.

*QUADS AR*

This is an augmented reality application for lower limb exercise, developed by Bluespot – The knee clinic. Through gamification the application motivates the user to execute a variety of exercises. The user interacts with augmented reality objects superimposed on a live real-world visual field. The application measures and records compliance and gives the opportunity to the user to share the data to health care professionals or on social media. (An augmented reality app for lower limb exercise - Shameem AC Sampath).

*Knee Pain Relieving Exercises*

This application is available on Google Store provided by Dr. Kavin Khatri. It is designed for people suffering from knee pain or arthritis of knee joint. The purpose of this application is through a set of exercises to strengthen the muscles in order to support better the joint and thus reduce the pain on the area.

*Arthritis Physio*

Arthritis Physio is an application available on Google Store that aims to strengthen the muscles in order to put less pressure on joints. Arthritis Physio is a compilation of exercises designed by a physiotherapist to improve strength and thus relieve the user from the OA pain. The app also includes information and answers to questions, like: How do I know I have osteoarthritis?

*Track + React*

Track + React is an application available on Google Store and Apple Store. This application helps the user to identify how his activities and habits are affecting the pain of osteoarthritis in order to help him change his habits for the better. It also permits the user to keep track of its nutrition, sleep, medication and exercise habits. Track + React keeps information in graphs.

*Jointfully Osteoarthritis*

Jointfully Osteoarthritis is available on Google Store and Apple Store. It helps the user to Track movement and activity goals, to get personalized reminders to stay on track with meds, to monitor pain levels, mood, weight and blood pressure and get video-tutorials for Physical Therapy.

### 4.5 Indoor Immobile Solution

During the gait retraining, data acquisition using hardware devices such as ground-reaction force-plates or force-measuring treadmills, motion capture cameras, and any other rehabilitation device, can usually take place only in laboratories and dedicated rooms. Further data processing and analysis can be conducted in the same room providing direct feedback both to the patient, healthcare experts and researchers. For that reason, we present an immobile solution of the gait intervention framework that can take place in such rooms.

Figure 28 presents a possible setup of the indoor gait retraining solution. The user is situated on a treadmill that measures the GRF. At the same time, a marker-based motion capture system records the position of the anatomical markers in order to reconstruct the motion of the segments. A projection screen can be used to visualize important variables and provide real time feedback to the user. Optionally, we can measure the EMG signals in order to enhance the quality of the model predictions. This setup can lead to accurate estimation of the kinematics and kinetics of the user, that can be used for validating both the developed models and the outdoor mobile solution that will be presented in the following subsection.

Figure 29 presents a high-level overview of the real-time simulation pipeline that would be used to extract the kinematic and dynamic quantities that would be provided to the personalized intervention system. The experimental measured maker positions are fed to the IK module, which determines the generalized model coordinates that best match the experimentally recorded motion. The kinematic analysis is very important for the next stages. Following Inverse Dynamics (ID) is performed to calculate the generalized forces (e.g. KAM) that satisfy the Equations of Motion (EoMs), provided any externally applied force. Static Optimization (SO) can be employed to estimate the required muscle activation and forces that satisfy both the motion and the physiological muscle constraints. This step can be further improved by using information from the EMG recordings if available. The muscle forces are important when one needs to compute the joint reaction loads. Finally, custom analysis will be performed to extract the variables required by the personalized intervention module.


Figure 28 Indoor immobile gait retraining solution, that is based on ground reaction treadmill, marker-based motion capture system and simple projection screen as a feedback device [9].

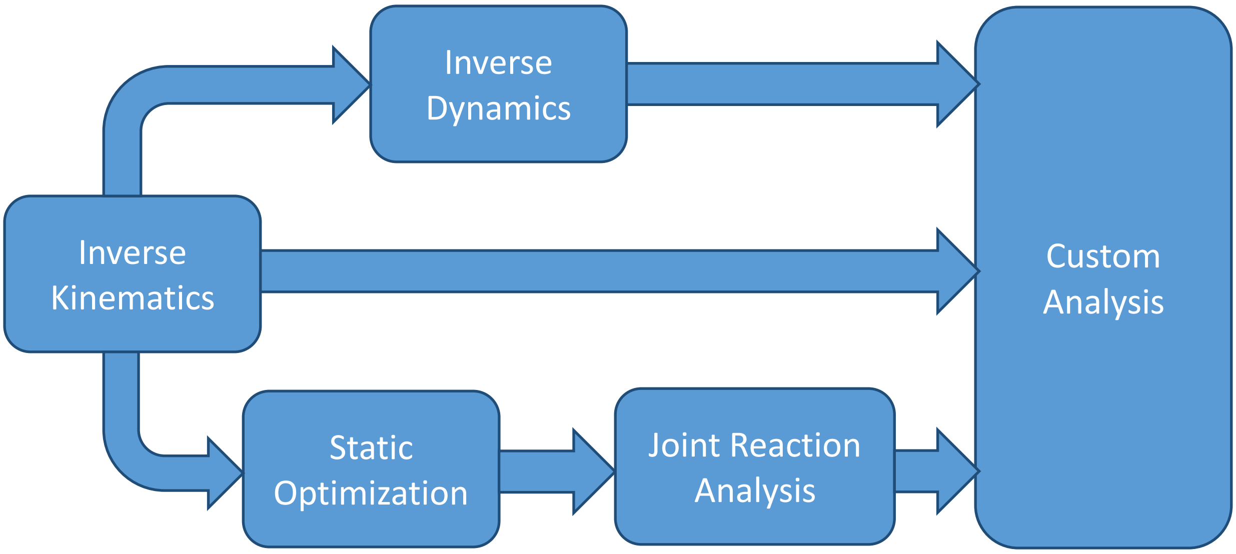



Figure 29 High-level overview of the real-time simulation pipeline that will be used to extract the variables for the personalized intervention module.

### 4.5.1 Inverse Kinematics

In order to perform any kind of IK analysis one must obtain the motion of the body segments from the recorded kinematics. The motion can be obtained either by recording the position of the attached markers or by measuring the 6D motion of IMUs. The next step would be to determine the evolution of the generalized model coordinates that best match the experimentally recorded motion. The IK method goes through each time step of the recorded motion and computes the generalized coordinates which positions the model in a pose that best matches the experimental marker. More formally, this is expressed as a weighted least squares problem, whose solution aims to minimize both marker and coordinate errors

$$\underset{\vec{q}}{\text{minimize}} \quad \sum_{i}^{\text{markers}} w_i \, ||\vec{x}_i^{exp} - \vec{x}_i(\vec{q})||^2 + \sum_{j}^{\text{coordinates}} \omega_j \, (q_j^{exp} - q_j)^2$$

where $w_i$ represents the weight for marker $i$, $\vec{x}_i^{exp}$ the experimental marker position, $\vec{x}_i(\vec{q})$ the model marker position that depends on the pose, $\omega_j$ the coordinate weight factor and $q_j^{exp}$, $q_j$ the experimental and model coordinates, respectively. The marker error is the distance between an experimental marker and the corresponding marker on the model. Each marker has a weight associated with it, specifying the influence of the particular term on the overall error. A coordinate error is the difference between an experimental coordinate value and the value computed by IK, that is optionally included if there is a priori knowledge on particular coordinates. The least squares problem can be solved using a general quadratic programming solver.

### 4.5.2 Inverse Dynamics

For the given kinematics describing the movement of a model and any externally applied force, the ID method determines the generalized forces (e.g., net forces and torques) at each joint that satisfy the movement. More formally (see equation bellow), are solved for the unknown $\vec{\tau}$ provided $\vec{q}$, $\dot{\vec{q}}$ and $\ddot{\vec{q}}$. Since $\vec{q}$ is calculated from IK, $\dot{\vec{q}}$ and $\ddot{\vec{q}}$ must be obtained using numerical differentiation. Discontinuities in the generalized coordinates can lead to numerical singularities during the evaluation of higher order derivatives and it is thus advised to apply filters to remove any undesirable artifacts [3]. The following notation is used for describing the EoMs

$$M(q)\ddot{q} + f(q,\dot{q}) = \tau$$

where $M \in \Re^{n\,x\,n}$ denotes the symmetric, positive definite joint space inertia mass matrix, $n$ the number of model Degrees of Freedom (DoFs) and $q, \dot{q}, \ddot{q}$ the joint space generalized coordinates and their derivatives with respect to time. The term $f$ models all internal and external applied forces (e.g., gravity, Coriolis, GRF, etc.), whereas $\tau$ the vector of applied generalized forces that actuate the model. Most of the quantities in the equations are a function of the generalized coordinates and derivatives, thus this dependency will be omitted for simplicity.

When ID is solved, it is preferred to ignore model constraints since a set of $\vec{\mathrm{q}}$, $\vec{\dot{\mathrm{q}}}$ and $\vec{\ddot{\mathrm{q}}}$ may not necessarily satisfy the constraint algebraic equations[1]. As a result, if a model contains kinematic constraints ID may give rise to unreliable estimates of the generalized forces. In this case, ID-based methods may provide a suitable solution. Another important misconception is that ID does not necessarily depend on externally applied forces, however, it is a common sense that they should be accounted for since their omission will significantly alter the result.

### 4.5.3 Static Optimization

As described in ID, the motion of the model is completely defined by the generalized positions, velocities, and accelerations. The SO uses the known motion of the model to solve the equations of motion for the unknown generalized forces $\tau$ subject to one of the following muscle activation-to-force conditions:

$$\underset{\mathrm{a}}{\text{minimize}} \sum_{\mathrm{m=1}}^{\mathrm{M}} {a_m}^p$$

$$\text{s.t.} \sum_{\mathrm{m=1}}^{M} a_m\, f_m^M\, r_{m,j} = \tau_j,\ \mathrm{j} = 1, \dots, \mathrm{n}$$

$$0 \le \mathrm{a_m} \le 1$$

where, $a_m$ is the activation level of muscle $m$, $p$ is a power factor typically 2, $f_m^M$ is the force produced by muscle $m$ and $r_{m,j}$ is the moment arm of muscle $m$ on joint $j$. There are totally $m$ muscle and $n$ joints. The objective of the optimization is to compute the minimal muscle activations $a_m$ needed so that the contribution of the muscle forces to the joint torques to be equal to the torques computed by ID for each time instance. It is called "static" optimization because the performance criterion (i.e., the cost index) is confined to quantities that can be computed at any instant in time during a simulation.

### 4.5.4 Joint Reaction Analysis

Joint Reaction Analysis (JRA) is used for calculating resultant forces and moments at joint. Specifically, it calculates the joint forces and moments transferred between consecutive bodies as a result of all loads acting on the model. These forces and moments correspond to the internal loads carried by the joint structure. These loads represent the contributions of all unmodeled joint structures that would produce the desired joint kinematics, such as cartilage contact and any omitted ligaments. The reaction load acts at

[1]For example, `OpenSim` ignores model constraints when performing ID calculations.

the joint center (mobilizer frame) of both the parent and child bodies. The loads can be reported and expressed in either the child, parent, or ground frames. The default behaviour is to express the force on the child in the ground frame.

### 4.6 Outdoor Mobile Solution

The immobile solution presented above, can be expensive, time consuming and cumbersome, especially for the patient. For that reason, we present here a mobile/outdoor solution that can potentially provide a more flexibility alternative to the indoor solution for the gait intervention framework.

Figure 30 presents a schematic diagram of the mobile gait retraining solution. Eight IMUs, designed and developed during WP5, will be attached to the body segments (foot L/R, shank L/R, thigh L/R, pelvis and torso) in order to collect information on motion of the patient. GRF shoes will be used to record the reaction forces between the ground and feet. AR glasses will be utilized to provide visual feedback to the user. Vibrotactile feedback could be also included in order to alert the user to correct his/her behaviour. The information would be transmitted to a station through wi-fi which will process the various information and provide real-time, personalized feedback. The visual feedback may target gait characteristics such as stride width, foot progression angle, trunk sway, etc., by providing differential cues through the feedback devices.

One of the technical challenges of this framework, as compared to the immobile solution, is the real-time reconstruction of kinematics (IK) from IMU measurements. More specifically, the IMUs can measure the linear and angular acceleration. IK requires position level information, thus the acceleration must be integrated twice, provided appropriate initial conditions. Unfortunately, different measurement errors can amplify and propagate resulting in inaccurate estimation of the position variables [10]. In addition, movement artefacts due to changes in the attachment positions of the sensors can induce errors it is thus important to validate this approach against the immobile solution.

The system that will be used by the station will be similar to the one developed for the immobile solution. The main difference will regard the IK module, for which a different approach will be adopted to solve the IK problem using IMUs information. Furthermore, the feedback devices that will be used by the mobile solutions will differ than the indoor solution, thus the differential cues that will be provided to the patient have to be adapted to the specific device used in each context (e.g., screen projection, AR glasses, vibrotactile, etc.).

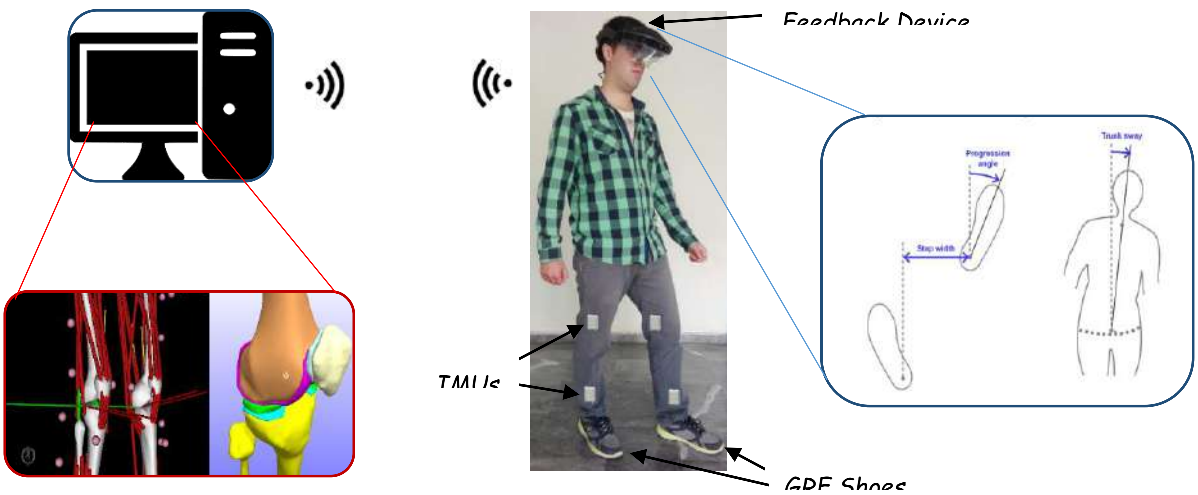


Figure 30 Mobile gait retraining solution that will collect and provide wireless, real-time and personalized intervention through AR and other feedback devices.

However, the development of such a solution presents difficulties regarding mainly the feasibility and the practicality of use. IMUs used in this setup are developed in prior work during WP5, in which the goal is primarily to acquire data related to behavior information and they were not intended for kinematic and dynamic analysis. Moreover, the user is required to wear additional hardware devices compared to the immobile solution, thus making it inconvenient for the user. These reasons, along with the technical challenges of this framework described above, lower the priority of its development as the potential of the mobile solution is yet to be explored.

### 4.7 Game Design Framework

The purpose of the game framework is to motivate and engage the users in physical activities. In this particular case, the purpose is to motivate the user to the gait retraining routine. By optimizing the walking ability of the individual, the pressure acting on the knee joint is reduced and thus not only the progression of OA is delayed, but also the pain is relieved. The user will be able to interact with the system that will provide the necessary information for a patient's specific gait. Performance statistics will be stored into the database system and processed accordingly by clinicians and Artificial Intelligence (AI) algorithms to adapt and refine the patient intervention strategy. Furthermore, this information will be presented to the user in a form of a progress report or to the clinician for evaluation (more details in section Nonetheless, an AR system can be employed to substitute the screen where the game is viewed. The purpose of using an AR system is to improve the interaction of the user with the application/game and enhance the user experience. By displaying virtual objects in the real environment, not only the user will better comprehend how to walk effectively, but also creates and environment that excites the user, stimulates his senses and thus motivating him to seek again for this "unique" experience.

As in the previous case, the JRA from the data and statistics from the wearable devices as well as the AI DSS must operate in real time, so that the participant has instantaneous feedback in order to closely follow his "virtual trainer" or to alarm him immediately whether he is executing an irregular – dangerous activity.

Additional objectives that we need to set for the design of the games are:

- The games must be easily understandable and they must not require any long technical manual or specialized tutorials. Users must quickly start trying them, and they must feel confidence and security while they play.
- The purpose of each game separately is to become a "habit" for the user. This means that users must come back on a regular or daily basis to commit mostly repetitive playing.
- Continuously give meaning, interest, and excitement to the users so they never become boring to play the games.
- The user must not feel anxious about the technology and the games must seem simple and without lags. For example, a simple progress bar is a great feature to help the users get through the waiting process. This makes it very clear what the site wants patients to do, how doing it, and emotionally rewards them for doing it.
- Achievements should be awarded for sticking to the desired behavior.
- Badges should be awarded for long-term performance after hitting some cumulative target.
- Levels as a measure of progress, with gradual "unlocking" of game features (e.g. advanced analytics, comparative evaluations), designed to engage the player in the early stages of the game.

Information Visualization). Gamification elements, such as rewards, achievements, scores, difficulty level, etc., would be also considered in order to improve the interaction and engage user to improve their physical activities. The effectiveness of this method will be further evaluated in the test campaign.

It is desirable that the system involves sensory feedback, such as IMU measurements, marker-based motion-capture cameras and ground reaction forces. In this case, this information can be transmitted to a station or to the smart device (smartphone) for processing in order to reconstruct the kinematics and dynamics in real-time. Provided this information, the system will be able to compare the performance of the user with respect to a desired profile and provide detailed guidelines for the correct execution of the gait. This information can also be used by the AI and simulation pipelines, in an offline mode, to provide detailed information on the contact pressure and other quantities of interest that can be used to refine the personal intervention strategy.

Finally, instead of displaying the game and the visual information on a screen the system can incorporate an element of AR feedback, in order enhance the user experience and effectiveness of the game. In this case, the system will provide visual cues and information statistics in real-time. This will result in correct execution of the gait and will motivate and engage the user to increase its daily physical activities. In the following paragraphs a more detailed explanation of the system is provided.

The gait – retraining activity is crucial for patients with OA. It is a promising conservative treatment for knee OA that can reduce knee loading and alleviate knee pain and consequently improve the individual's quality of life. Nevertheless, in order to motivate and encourage the patients to exercise and entertain, games are employed. In fact the gait retraining activity will be ideally adapted to the games' playing script. The user's physical performance and tolerance will be accounted by the game, in order to adjust the positioning of the patient and duration of the training. Several features that the game must have in order to motivate the user [11], are the following:

- Enactive mastery experiences (e.g., goal setting, discussion of performance and progress)
- Vicarious experiences (e.g., role modeling, storytelling)
- Verbal persuasion (e.g., education, support, encouragement)
- Physiological and effective feedback (e.g., monitoring the emotional and physical burden, managing discomfort).

The execution of the training will mainly involve a treadmill and a screen where all the visual information will be displayed, whether that involves information about the performance of the participant and the correct way of walking or graphics relevant to the game. To avoid injuries, it is imperative that the application's user interface provides a friendly, flexible and easily comprehensible environment that graphically demonstrates how the training must be carried out, with the appropriate instructions also displayed.

To evaluate the performance of the participant, some sensory feedback is also required in order to capture the motion of the user. The feedback can be derived either from wearable sensors, like IMUs, or they can arise from a force - sensing treadmill that can measure the GRFs. This information is essential to reconstruct the human posture at every instant and to perform JRA. Thus the application will upload data concerning the joint position/velocity/acceleration and/or the GRF on a server that will be responsible to perform JRA and also estimate the posture of the participant. After the JRA is performed and the forces between the joints have been determined, an AI DSS will be responsible to design the gait retraining exercise for a particular user, based on the JRA results and the individual's specific anatomy. The output of the DSS will be transmitted from the server to the application in order to inform the user how well he is performing the exercise and what adjustments he should make. The reason why the JRA is better implemented on a remote server and not on the mobile device is due to the performance limitations of the mobile devices, which make it nearly impossible to acquire real time data.

Additionally, the data stored on the server, with the consent of the user will be available to the clinician, for further evaluation. Through an interface/application on his personal computer he can have access to the database of the user and he will be able to reconstruct the motion of the participant, visualize the forces that acted on the joints and determine which muscle groups are activated. So, in any situation that he detects an irregular activity he can intervene either by overriding the specifications of the DSS with his own preferences or by demonstrating the participant how the gait is carried out correctly.

Nonetheless, an AR system can be employed to substitute the screen where the game is viewed. The purpose of using an AR system is to improve the interaction of the user with the application/game and enhance the user experience. By displaying virtual objects in the real environment, not only the user will better comprehend how to walk effectively, but also creates and environment that excites the user, stimulates his senses and thus motivating him to seek again for this "unique" experience.

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- Levels as a measure of progress, with gradual "unlocking" of game features (e.g. advanced analytics, comparative evaluations), designed to engage the player in the early stages of the game.

# 5 Information Visualization

The information visualization system of OACTIVE, is an essential element of the Personal Guidance System of OACTIVE AR gaming environment, since it will enable the end users to visualize physiological and behavioural parameters provided by the OACTIVE system. The aim is to provide the key information, in an optimal way to both end user groups, namely patients (elderly people, athletes) and healthcare experts. Thus, the Information Visualization system will include two different front-ends targeting the two different end-user groups of OACTIVE. The patient front-end will include intuitive visualizations (based on visual analytics techniques) of parameters that patients can understand, while the clinician front-end will provide more complex representations to the clinical team. Visual analytics techniques will be employed for the delivery of different perspectives of sub-graphs of the correlated data and models, so that the different end-users can receive role-specific (personalised) and goal-oriented representations of the medical information. Furthermore, standard interaction techniques will be implemented, including selection, panning, highlighting zoom in/out based on open source tools (with OpenGL). A more detailed presentation of the aforementioned functionalities and interfaces is presented in the rest part of this section.

## 5.1 Web Front-End

Registered users will have access to a web-platform that will display information about all exercise sessions performed by patients, sorted by time and organized in a calendar, enabling the users, both patients and healthcare experts, to review performance in all metrics, make comparisons and correlations.

The interface of mobile application will provide users with meaningful feedback about their performance, in the context of exercises and games included in the personalized gait retraining and rehabilitation strategy of the subjects. All the available metrics will be stored, analyzed and presented to the users of the system using visual analytics, in order to engage the subjects and provide clinicians with useful performance indicators that can be used to evaluate and modify the intervention methods.

The specific interface will include game elements and exercise sessions info to motivate subjects to adhere their treatment plan and perform correctly all phases of interventions towards the improvement of their health condition.

Game elements of this interface will include:

- Simple Points (SPs): points for rating the game performance and the effort of the patient for the performance of movements in a game session
- Golden Points (GPs): points calculated based the "experience" of the participant, earned with the participation and successful completion of other game sessions by the user. The aim is to keep subjects engaged in a continuous upward process towards the achievement of the intervention specific objective, for the individual patient.
- Collection of Rewards (CoR): rewards provided by OACTIVE game as a positive, unexpected feedback to the user.
- Performance Goal (PG): is the objective of the intervention, translated to game objective, set by the clinician and with difficulty level determined by limitations, status, achievements and progress of individual patient.
- Questions that if answered correctly by the patient, rewards will be added to his/her CoR
- Visual sense of progress and achievements with the use of avatar images

Each patient will have access to the above game elements through his/her personal dashboard and through a Login UI. This personal dashboard will be tailored to the target patient group (athletes and elderly people with developed OA) and will be composed by the following features: i) patient profile , ii) gaming section, with description of the game and game elements (e.g. game level, collected points and rewards) iii) exercises section , with description of exercises included in each game, the goal of the performed movements and an overview of daily, weekly and global progress, as well as future trends of his/her situation, iv) Education, Information and Training section with tips and messages sent by the OACTIVE system for guidance, as well as questions to be answered by filling in appropriate forms, towards the collection of additional rewards, and v) Virtual Guidance Agent (avatar) that will provide suggestions and support to the user. By selecting a specific game from a menu, the patient will be able to view collected points and rewards by clicking on the corresponding icons, while a bar graph will appear with segments to distinct the subject's performance in the included exercises. Info will pop up by selecting the segment of the bar. Visualizations of the movements will be provided and will be accompanied with text and audio information (such as goal, level of exertion, duration, number of repetitions), charts of the difference between sensed and real-time simulated parameters (such as step length, step time, vertical forces, hip angles, ankle moment, hip flexion, abduction and extension, etc.), as well as with gait metrics for elderly people, and rehabilitation metrics for athletes in post-traumatic OA. The above information will be presented and explained to the patient by an avatar of his/her choice, that will appear in the various steps of the exploration process as one of the OACTIVE system element which will transmit information and advices to the users in a friendly manner, will give suggestions and it will support the users in their tasks with interactive features.

Clinicians' interface will display both categories of patients: elderly people with developing OA and athletes in post-traumatic OA. For each category, the clinicians will have the option to sort the patients based on their severity additionally to other aspects such as alphabetical order, recent patient activity, personal information, etc. Clinicians will be able to access information associated to recordings and metrics for each patient. These will include representations of exploration results (identification of patterns, estimation of relationship between variables, identification of correlations among variables), predictions of future trends and risks, and will assist health professionals to evaluate progress throughout the rehabilitation process and identify the need for specific modifications to better adapt the intervention strategy to the specific patient therapeutic needs and limitations. The clinician will be able to set the movement controls desired, for example postural inclination, or elbow flexion tolerance, to edit the questions to be answered by the patients, as well as to configure game aspects such as the number of repetitions and degrees of improvement from one level to another. Indicators about adherence will be also shown in the clinicians' interface, in relation to the overall programme as the percentage of sessions done and, but also in relation to each specific session in terms of percentage of time within prescribed thresholds.

Through special controls in the interface, customization options will be offered to the users, such as cosmetic assets (e.g. avatar, profile page/image), interface elements and behaviour (e.g. audio volume, GUI theme), game-related components (e.g. status messages, usage of in-game accumulated points), avatar etc. Users will be able to highlight text, zoom in and out and extract information in different formats

### 5.2 Mobile Front-End

The personal guidance application will provide direct (real time) feedback to patients, either in the heads-up-display (HUD) or directly in the smartphone screen. The information that can be rendered in a way to also be visible to the user is limited by the phone's screen size.

Data will be collected from wearable sensors and from motion capture cameras and will be processed by dedicated module towards the identification of deviations of measured parameters from the expected values, towards the identification of errors during the exercise sessions that will trigger the delivery of guidance/tips to help the user avoid incorrect movement execution.

The main functionalities of the mobile front-end are:

- Representation of the exercise performance and of the patient's effort for the execution of movements, through an increased coloured bar.
- Instructions to avoid incorrect movements, represented with green and red arrow heads for optimal and non-optimal shifts.
- Congratulations message. When the user achieves a certain number of points, a congratulations visual message will be shown
- Additional instruction in auditory form

For the two patient target groups of the project (athletes and elderly people with developed OA) two HUD modes will be developed: i) HUD for post-traumatic athletes with developed OA, and ii) HUD for elderly people with developed OA. Metrics of highest importance will be displayed with higher size and centered, while metrics of lower importance will have a more discrete design. Some special widgets will be displayed all the time with small icons or text and will be updated with higher intervals, like percentage of correct movements, time left. A pop up is displayed during some of the update phases for these widgets in order to be easily visible for the user. These widgets are common for all HUD modes and they are:

- Percentage of correct movements, time left
- Gamification elements (Points, rewards)
- Pop ups for guiding messages and tips

Visualization of all necessary data will be in a robust augmented reality environment, by i) accurate tracking of the real-world coordinate system to correctly register visual content within the user's view (augmented reality glasses case), ii) accurate projection of visual content to the user's HUD. Additionally, all necessary information should be displayed, considering the limited screen size. (heads up display case).

# 6 Concluding Remarks

This document presented an overview of the personalized intervention system, including the gait retraining and the information visualization system. While this deliverable presents an ambitious plan for the WP7, the usefulness and feasibility of the presented solutions will be further discussed and evaluated according to the goals of the OACTIVE project and the progress of the different WPs. A brief discussion on future directions and issues that may arise is presented below.

One of the most important parts of WP7 is the implementation of a personalized gait retraining system, as the developed system will be used by the healthcare experts to examine the potential of delaying the progression of the OA disease. At the same time, from a technical perspective, it is important that the various analyses can be performed in real-time such that the system can be able to provide adequate personalized feedback to the end user. The robustness and accuracy of the estimated kinematics and dynamics depend heavily on the robustness and performance of the motion acquisition system that will be used. To this end, OACTIVE targets at implementing two solutions, namely (i) an immobile approach based on standardized equipment (marker-based MOCAP and treadmill) that can provide accurate reconstruction of the movement but with frequent usage constraints, and (ii) a mobile solution that can be employed in an outdoor environment (extensive usage), which however, may not be able to predict the required variables with the desired high accuracy. The development of the immobile solution is of high priority, while the potential of the mobile solution will be explored when the behaviour IMU system is developed in WP5. It should be emphasised that the goal of the system developed in WP5 is to acquire behaviour information and it was not initially intended for kinematic and dynamic analysis.

Regarding the immobile solution for the gait retraining, the core components will include a force-sensing treadmill, marker-based motion-capture cameras, and a screen-projector and AR smart-glasses for the depiction of the game-like interactive application. Optional additives to the setup could include EMG measuring system and vibrotactile feedback devices. Many of the hardware devices described in section 4.1 are suitable for usage in the setup. For example, we concluded that the Meta 2 AR glasses best satisfy the needs of the immobile solution since it provides the computational power of a desktop computer. However, the choice of the majority of the devices depends heavily on their availability by the partners of the OACTIVE project, namely the force-sensing treadmill and the marker-based motion-capture cameras. On the other hand, the aim of our implementation of the personalized gait retraining system is to be independent from the choice of hardware devices and be able to transfer across different devices from different manufactures, thus providing freedom on the choice of the final setup.

As for the mobile solution, we have described the basic architecture that comprises of the GRF pressure shoes, IMUs and AR glasses, with the optional addition of EMG measuring system and vibrotactile feedback devices. In section 4.1 we presented some of the available devices that can be used in this setup, however we concluded that not every device fulfils the requirements of the desired solution, mainly due to their restricted nature of data acquisition and processing through dedicated SDKs. Instead, the development of custom devices will allow a more flexible configuration that assure adequate scalability and can fit best to the project requirements. For example, the design and development of IMUs will be conducted by SMARTEX during the WP5. These specific implementations will allow better low-level design and development and consequently will provide more freedom over the whole architectural design.

Considering the modelling, kinematic and dynamic analysis and game development, any desktop with enough computational power that can meet the minimum system requirements of the used software, will suffice for the needs of the application. Whilst, the interactive applications can run in any commercially available tablet or smartphone, which are easily accessible by both healthcare experts and patients.

Concerning the software for the development of the games we have resolved that Unity 3D satisfies better our requirements to build functional game elements with effective and easy troubleshooting. The reason for that is derived from the fact that Unity 3D is not only the top design toolkit for games, having a vast community of developers that share their knowledge by providing solutions, but also comes with a huge collection of virtual objects that can be easily be integrated into our application. Additionally, Unity 3D offers great flexibility for the development of AR application since it integrates the Vuforia Engine, through which the development of AR applications for mobile devices is straightforward. As for the case of physics engine, we have decided that the best choice is OpenSim. The advantages of using OpenSim among the other engines are that it is open source, it offers high accuracy, we have great expertise with its environment, it fulfills our requirements for IK/ID analysis and JRA, we can use publicly available code or models developed by other users and it supports the creation of custom models. Thus, by using OpenSim to make our analysis, eventually we will make public to the community our own developed model, so other users can test it.

Finally, some minor consideration regarding the information visualization subsystem. As the OACTIVE project will collect, process and produce a large set of data, it is important to create a system which will not overload the clinician with plenty of information. Even if, we are tempted to employ techniques steaming from visual analytics to extract information from heterogeneous high-dimensional data, we must bear in mind the practical aspects of the system, considering that the user must be trained to use these technologies. Therefore, we should aim to create an intuitive interface that will extract the relevant information that is important for the clinician/patient and present it in the simplest possible way.

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**Disclaimer**

# 9 Appendix

In this section, a list of tables with the detailed technical specifications of the hardware devices presented in sections 4.1 and 4.3 is given.

## 9.1 Gait Retraining: Hardware Devices – Technical Specifications

### 9.1.1 Inertial Measurement Units

***Xsens MTw Awinda IMU System (Xsens Technologies BV, Enschede, NL)***

Table 2. Technical Specifications of Xsens' MTw Awinda IMU System

| **MTw Awinda** | | | |
|---|---|---|---|
| Tracker placement | Easy fastening with Velcro straps | | |
| Internal sampling rate | 1000 Hz | | |
| Latency | 30 ms | | |
| Buffer time (retransmissions) | 10 s | | |
| Battery | LiPo, 6 Hours (continuous use) | | |
| Dimensions Tracker | 47 x 30 x 13 mm (1.85 x 1.18 x 0.51 in) | | |
| Weight | 16 g (0.56 oz.) | | |
| Operating temperature range | 0°C - 50°C | | |
| **Communication** | | | |
| Range | Awinda station | Awinda dongle | |
| Open space | Up to 50 m (165 ft.) | Up to 20 m (65 ft.) | |
| Office space | Up to 20 m (65 ft.) | Up to 10 m (33 ft.) | |
| Wireless protocol | Xsens patented Awinda protocol | | |
| Receiver | Awinda Station / Awinda Dongle | | |
| **Orientation** | | | |
| Static Accuracy (Roll/Pitch) | 0.5 deg RMS | | |
| Static Accuracy (Heading) | 1 deg RMS | | |
| Dynamic Accuracy (Roll/Pitch) | 0.75 deg RMS | | |
| Dynamic Accuracy (Heading) | 1.5 deg RMS | | |
| **Tracker components** | | | |
| | Angular velocity | Acceleration | Magnetic field |
| Dimensions | 3 axes | 3 axes | 3 axes |
| Full scale | ± 2000 deg/s | ± 160 m/s2 | ± 1.9 Gauss |
| **Awinda station** | | | |
| **Operating temperature range** | | | |
| Ambient | -25°C - 80°C | | |
| Specified Performance | 0°C - 65°C | | |
| Specifications for non-condensing environment | Avoid wet and humid conditions | | |
| Power Supply | EU/US/UK power adapters provided | | |
| **Communication** | | | |
| Awinda Station | PC Interface: USB | | |
| **Physical Properties** | | | |
| Dimensions (without antenna) | 148 x 104 x 31.9 mm<br>(5.8 x 4.1 x 1.3 in) | | |
| Weight | 200g (7 oz.) | | |
| **Synchronization with third party devices** | | | |

| | |
|---|---|
| 4 BNC connectors | - 2 for sync in<br>- 2 for sync out |
| TTL pulses | 0-3.3V levels |
| Software configurable | Yes |
| **Wireless update rates** | |
| 1 MTw | 120 Hz |
| 5 MTw | 120 Hz |
| 9 MTw | 100 Hz |
| 10 MTw | 80 Hz |
| 20 MTw | 60 Hz |
| **Awinda Dongle (Miniature version of Awinda Station)** | |
| Dimensions | 20.4 x 45 x 10.6mm (0.8 x 1.8 x 0.4 in) |
| Weight | 8g (0.28 oz.) |

### *NGIMU (x-io Technologies, UK)*

Table 3. Technical Specifications of x-io Technologies' NGIMU

| | |
|---|---|
| **On-Board Sensors** | |
| Gyroscope | Range: ±2000°/s |
| | Resolution: 0.06°/s |
| | Sample Rate: 400 Hz |
| Accelerometer | Range: ±16 g |
| | Resolution: 490 µg |
| | Sample Rate: 400 Hz |
| Magnetometer | Range: ±1300 µT |
| | Resolution: ~0.3 µT |
| | Sample Rate: ~20 Hz |
| Barometric Pressure | Range: 300 hPa to 1100 hPa |
| | Resolution: 0.18 Pa |
| | Sample Rate: ~25 Hz |
| Humidity | Range: 0% to 100% |
| | Resolution: 0.008% |
| | Sample Rate: ~25 Hz |
| Temperature | There are 3 sensors to measure the temperature of the CPU, inertial sensors, and environmental sensors. The temperature sensors are not intended to provide an accurate measurement of ambient temperature. |
| **AHRS Algorithm** | |
| Outputs | Quaternion, Rotation Matrix, Euler Angles, Linear Acceleration, Earth Acceleration |
| Update Rate | 400 Hz |
| Static Accuracy (Pitch/Roll) | <1° RMS |
| Static Accuracy (Heading) | <2° RMS |
| **Analogue Inputs** | |
| Channels | 8 |
| Range | 0 V to 3.1 V |

| | |
|---|---|
| Resolution | 12-bit |
| Sample Rate | 1 kHz |
| **Auxiliary Serial Interface** | |
| Baud Rate | All standard baud rates and arbitrary baud rates from 7 baud to 12 Mbaud |
| Hardware Flow Control | None or RTS/CTS |
| Voltage | 3.3 V (RS-232 tolerant) |
| Packet Framing | Buffer Size, Timeout, Framing Character |
| **Mechanical** | |
| Board only | Size: 50 × 33 × 8 mm |
| | Weight: 10 g |
| Assembled with battery in housing | Size: 56 × 39 × 18 mm |
| | Weight: 46 g |

### 9.1.2 Ground Reaction Force Plates

***Multicomponent Force Plate Type 9281E***

Table 4. Technical Specifications of Kistler's Multicomponent Force Plate Type 9281E

| **Technical Specifications** | | | |
|---|---|---|---|
| **Technical Data** | | | |
| Dimensions | | mm | 600x400x100 |
| Measuring range | Fx, Fy | kN | –10 ... 10 |
| | Fz | kN | –10 ... 20 |
| Overload | Fx, F | kN | –15/15 |
| | Fz | kN | –10/25 |
| Linearity | %FSO | | <±0,2 |
| Hysteresis | %FSO | | <0,3 |
| Crosstalk | Fx <-> Fy | % | <±1,5 |
| | Fx, Fy –> Fz | % | <±1,5 |
| | Fz –> Fx, Fy | % | <±0,5 (inside sensor rectangle) |
| Rigidity | x-axis (ay = 0) | N/µm | ≈250 |
| | y-axis (ax = 0) | N/µm | ≈400 |
| | z-axis (ax = ay = 0) | N/µm | ≈30 |
| Natural frequency | fn (x, y) | Hz | ≈1 000 |
| | fn (z) | Hz | ≈1 000 |
| Operating temperature range | | °C | 0 ... 60 |
| Weight | | kg | 16 |
| Degree of protection | EN 60529:1992 | | IP65 |
| **Force Plate with Built-in 8-Channel Charge Amplifier, Type 9281EA** | | | |
| Calibrated range | Fx, Fy | kN | 0 ... 5 |
| | Fz | kN | 0 ... 20 |
| Calibrated partial range | Fx, Fy | kN | 0 ... 1,25 |
| | Fz | kN | 0 ... 5 |
| Sensitivity range 1 | Fx, Fy | mV/N | ≈40 (nominal value) |
| | Fz | mV/N | ≈18 (nominal value) |

| | | | |
|---|---|---|---|
| Sensitivity range 4 | Fx, Fy<br>Fz | mV/N<br>mV/N | ≈2,0<br>≈0,9 |
| Ratio ranges 1:2:3:4 | | | 1:5:10:20 (±0,5 % accuracy) |
| Threshold | | mN | <250 (only range 1) |
| Drift | | mN/s | <±10 |
| Supply voltage | | VDC | 10 ... 30 |
| Supply current | | mA | ≈45 |
| Output voltage | | V | 0 ... ±5 |
| Output current | | mA | –2 ... 2 |
| Control inputs (optocoupler) | | V | 5 ... 45 |
| | | mA | 0,4 ... 4,4 |
| **Force Plate without Charge Amplifier, Type 9281E** | | | |
| Calibrated range | Fx, Fy<br>Fz | kN<br>kN | 0 ... 10<br>0 ... 20 |
| Calibrated partial range | Fx, Fy<br>Fz | kN<br>kN | 0 ... 1<br>0 ... 2 |
| Threshold | Fx, Fy, Fz | mN | <50 |
| Sensitivity | Fx, Fy<br>Fz | pC/N<br>pC/N | –7,5 (nominal value)<br>–3,8 (nominal value) |

### *AccuGait Optimized (AMTI, Watertown, MA)*

Table 5. Technical Specifications of AMTI's AccuGait Optimized

| | |
|---|---|
| Dimensions (WxLxH) | 502 x 502 x 45.47 mm |
| Weight | 11.36 Kg. |
| Channels | Fx, Fy, Fz, Mx, My, Mz |
| Top plate material | Composite |
| Temperature range | -17.78 to 51.67°C |
| Mounting hardware | Not Required |
| Amplifier | Built-in |
| Sensing elements | Hall Effect |
| Analog outputs | Not Available |
| Digital outputs | 6 Channels |
| Interface | USB 2.0 |
| Device Synchronization | Automatic; ultra-low jitter |
| Filters | Fixed 100 Hz 3rd order analog |
| Power Supply | USB-powered, 380mA |
| Digital Data Rate | 10 – 1000 data sets per second, user selectable |
| External Sync Signal | Active = low volts, switch to ground<br>Inactive = high volts, open circuit with internal pull up resistor. Protected to ± 10V. 1K Ohm input resistance. |
| Digital Data Transmission | 32bit floating point data containing 6 measurement channels, IEEE format |
| Computer Requirements | USB 2.0 port, Windows 7, 1024 Mb RAM, 1.7 GHz |
| Software Force Platform Capacity | NetForce™: up to 12 force platforms (USB hubs |

| | |
|---|---|
| | required)<br>BioAnalysis™: up to 4 force platforms (USB hub required) |
| CE Certification | CE Compliant – Medical Grade – Passed AAMI/ES 60601-1, CAN/CSA C22.2 #60601-1, IEC 60601-1, & IEC 60601-1-6 |

| Channel | Fx | Fy | Fz | Units | Mx | My | Mz | Units |
|---|---|---|---|---|---|---|---|---|
| Capacity | 445 | 445 | 1334 | N | 226 | 226 | 85 | N-m |
| Sensitivity | 0 | 0 | 0 | µv/v-N | 0 | 0 | 0 | µv/v-N-m |
| Natural frequency | 140 | 140 | 150 | Hz | - | - | - | Hz |

### *F-Scan (Tekscan, Inc. South Boston, MA)*

Table 6. Technical Specifications of Tekscan's F-Scan

| Sensors | Standard | Long-Handle | Sport | XL |
|---|---|---|---|---|
| Insole Size | Up to 14 Mens (US) | Up to 14 Mens (US) | Up to 14 Mens (US) | Up to 24E Mens (US) |
| Thinness | 0.15mm/0.007 in | 0.15 mm/0.007 in | 0.406 mm/0.016 in | 0.406mm/0.016 in |
| Technology | Resitive | | | |
| Resolution | 3.9 per cm² / 25 sensels per in² | | | |
| Pressure Range | 50-75 PSI / 345-517 kPa (sensitive) to 125 PSI / 862 kPa (standard) | | | |

| Systems | Base (tethered) | Wireless | Datalogger |
|---|---|---|---|
| Electronics Included | 2 VersaTek Cuffs<br>VersaTek 2-Port Hub | 2 VersaTek Cuffs<br>1 VersaTek Wireless Unit | 2 VersaTek Cuffs<br>1 VersaTek Datalogger Unit |
| Scan Rates | Up to 750 Hz | Up to 100 Hz | Up to 750 Hz |
| Max Distance from PC | 15 M / 50 ft standard, Up to 30.5 M / 100 ft available | Up to 100 M/328 ft | Unlimited |
| Connection | USB | Wi-Fi | Upload via USB |
| Power | 0.35 A, 100-240 VAC, 50 - 60 cycles | Li-Ion Battery, 8V / 2400 mA-Hr | Li-Ion Battery, 8V / 2400 mA-Hr |
| **System** | | **Wireless/Datalogger Unit** | |
| Size | | 4.20 x 3.75 x 1.50 in (10.7 x 9.5 x 3.8 cm) | |
| Weight | | 322 g / 11.4 oz (with belt & battery) | |
| Battery Life | | Up to 2 hours recording | |

### *The pedar® system (novel.de, Munich, GE)*

Table 7. Technical Specifications of novel.de's pedar® system

| pedar®-xf system | |
|---|---|
| dimension (mm) | 150 x 100 x 40 |
| weight (g) | 400 |
| number of sensors (max) | 256 (1,024) |

| | |
|---|---|
| measurement frequency | 20,000 sensors/second |
| storage type | 2 GB SD card |
| computer interface | fiber optic/USB and Bluetooth |
| operating system | current Windows OS |
| sync option | fiber optic/TTL, in and out/wireless |
| power supply | NIMh battery |
| **pedar® insoles** | |
| shoe size | 22 to 49 (European), 3 widths |
| thickness (mm) | 1.9 (min. 1) |
| number of sensors | 85 - 99 |
| pressure range (kPa) | 15 - 600 or 30 - 1,200 |
| hysteresis (%) | < 7 |
| resolution (kPa) | 2.5 or 5 |
| offset temperature drift (kPa/K) | < 0.5 |
| minimal bending radius (mm) | 20 |

### 9.1.3 Force-Sensing Treadmills

***Fully Instrumented Treadmill (FIT) (Bertec, Columbus, Ohio)***

Table 8. Technical Specifications of Bertec's Fully Instrumented Treadmill (FIT)

| | |
|---|---|
| Instrumented treadmill | 81.1 x 54.6 x 15.3 |
| Max Allowable Load, N (lb) (per treadmill side) | 6,675 (1500) |
| Max Load Range, N (lb) | Fx, Fy: 2,225 (500)<br>Fz: 4,450 (1,000) |
| Speed Range, km/h (mi/h) | 0-24 (0-15) |
| Acceleration, $m/s^2$ ($ft/s^2$) | 0-25 (0-82) |
| Max Sound Level | 90 dB |
| Number of Belts | 2 |
| Size of Belts | Two independent force measuring running belts, approximately 1.75 m (70 in) long and 0.5 m (20 in) wide per belt. |
| Walking Surface, m (in) | 1.75 x 1 (approx. 70 x 40) |

***AMTI Force-Sensing Tandem Treadmill (AMTI, Watertown, MA)***

Table 9. Technical Specifications of AMTI's Force-Sensing Tandem Treadmill

| | |
|---|---|
| **Integrated Force Plate Specifications** | |
| Vertical Force Plate Capacity | 8800 N |
| Horizontal Force Plate Capacity | 4500 N |
| Linearity | +/- 0.2 % full scale output |
| Hysteresis | +/- 0.2 % full scale output |
| **Treadmill Dimensions** | |
| Working Surface of Each Belt | 74 (L) X 66 (W) cm |
| Total Working Surface | 148 (L) X 66 (W) cm |
| Non-Inclined Height | 28 cm |

| | |
|---|---|
| Overall Dimensions (Including Handrails) | 203 (L) X 112 (W) X 125 (H) cm |
| Front Handrail Supports (Fixed) | Two posts, 91 cm high and 91 cm apart |
| Weight | 400 kg |
| **Power Requirements** | |
| 208 VAC, 3-phase, WYE connected 20-Amp twist lock receptacle. | |
| **General** | |
| Speed | 0-20 kilometers per hour adjustable in 0.06 kilometer per hour increments |
| Elevation | Up to 25% grade |
| Installed force platform resonant frequency | 300 Hz (Fx, Fy End-to-End model) |
| Reversible belt direction for uphill and downhill walking and running. | Yes |
| Removable side and front handrails. | Yes |
| One instrumented force platform (Fx, Fy, Fz, Mx, My and Mz) under each belt. | |
| Analog and digital outputs available for each force platform through supplied GEN5 amplifiers | |

### 9.1.4 EMG Measuring System

***EMG Bluetooth measuring system (zebris Medical GmbH, Isny im Allgäu, GE)***

Table 10. Technical Specifications of zebris' EMG Bluetooth measuring system

| | |
|---|---|
| **Basic device** | |
| Number of analog channels | 8 |
| Number of digital channels | 4 |
| Measuring rate | 1000 Hz per channel |
| Resolution | 12 bit |
| Internal backup memory | 512 kB |
| Data backup if reception is interrupted | 1 min (4 channels, 1000 Hz) |
| Power supply | 4x batteries type AAA 1,5 V |
| Dimensions B x H x T | 90 x 130 x 38 mm |
| Weight (without batteries) | 150 g |
| **Active differential electrode cables** (obtainable with or without neutral electrode) | |
| Up to eight electrodes can be connected to the basic device | |
| Supply voltage | +-5 V bis +-15 V |
| Input impedance | 10 E + 12 Ω |
| CMRR | 110 dB |
| Noise-related input | 0.28 µV |
| Voltage gain | 1000 |
| band width | 7 bis 500 Hz (anti-aliasing low-pass filter) |
| Dimensions B X H x T | 23 x 9 x 30 mm |
| Length of cable | 1,45 m |
| **System requirements** | |
| Microsoft Windows XP Service Pack 2 (minimum requirement), USB interface for Bluetooth adapter included in the delivery | |

Compatible with Noraxon MyoResearch XP analysis software

### Shimmer3 EMG Unit (Shimmer, Boston, USA)

Table 11. Technical Specifications of Shimmer's Shimmer3 EMG Unit

| | |
|---|---|
| Gain | software configurable (1, 2, 3, 4, 6, 8, 12) |
| Data rate | software configurable (125, 250, 500, 1000, 2000, 4000, 8000 SPS) |
| Input differential dynamic range | approx 800 mV (for gain = 6). |
| Bandwidth | 8.4 kHz |
| Ground | Wilson Type Driven Ground |
| Input Protection | ESD and RF/EMI filtering; Current limiting; inputs include defibrillation protection (survive only, not repeat) |
| Connections | Input Ch1N, Input Ch1P, Input Ch2N, Input Ch2P, Reference (Ref) |
| All Hospital-Grade 1mm Touchproof IEC/EN 60601-1 DIN42-802 jacks. | |
| Ultra-lightweight | 31 grams |
| Compact Dimensions | 65 x 32 x 12 mm |
| EEPROM memory | 2048 bytes. |

#### 9.1.5 Vibrotactile Feedback Devices

### C-2 Tactor (Engineering Acoustics, Inc., Casselberry, FL)

Table 12. Technical Specifications of Engineering Acoustics' C-2 Tactor

| | |
|---|---|
| Physical Description: | 1.2" diameter by 0.31" high |
| Weight | 17 grams |
| Exposed Material: | anodized aluminum, polyurethane |
| Electrical Wiring: | Flexible, insulated, #24 AWG. |
| Skin Contactor: | 0.3" diameter, pre-loaded on skin. |
| Electrical Characteristics: | 7.0 ohms nominal. |
| Insulation Resistance: | 50 megohm minimum at 25 Vdc, leads to housing. |
| Response Time: | 33 ms max |
| Transducer Linearity: | +/- 1 dB from sensory threshold to 0.04" peak displacement. |
| Recommended Drive: | Sine wave tone bursts 250Hz at 0.25A rms nominal, 0.5 A rms max for short durations. |
| Recommended Driver: | Bipolar, linear or switching amplifier, 1 W max, 0.5 W typical. |

### 9.1.6 Motion Capture Cameras

***Vicon Vantage V16 (Vicon, Oxford, UK)***

Table 13. Technical Specifications of Vicon's Vicon Vantage V16

| Model | V16 |
|---|---|
| Resolution (MP) | 16 |
| Max Frame Rate (Hz) | 120 @ 16MP |
| Max Frame Rate (Hz) | 2000 |
| On-Board Marker Processing | Yes |
| Standard Lens | 18 mm |
| Wide Lens | 12.5 mm |
| Minimum Standard FOV (H x V)° | 54.7 x 54.7 |
| Minimum Wide FOV (H x V)° | 76.4 x 76.4 |
| Camera Latency | 8.3 ms |
| Strobe | IR |
| Shutter Type | Global |
| Connection Type | Cat5e / RJ45 |
| Power | PoE+ |
| Max Power Consumption | 24W |
| Dimensions (mm) (H x W x D) | 166.2 x 125 x 134.1 |
| Weight (Kg) | 1.6 |
| Updateable Firmware | Yes |

***Kestrel 4200 (Motion Analysis Corp., Santa Rosa, CA)***

Table 14. Technical Specifications of Motion Analysis' Kestrel 4200

| **CAMERA** | |
|---|---|
| Frame size (pixels) | 4.2 megapixels |
| Resolution | 2048 x 2048 |
| Frame rate at full resolution | 200 fps |
| Sensor maximum frame rate | 9,500 fps |
| Shutter type | Global Shutter |
| Standard lens | 12.5mm, 12-36 mm Zoom |
| Camera power supply | HCP-8 |
| Camera connectors | Ethernet, Sync in/out |
| Camera cabling | Standard Cat5E, power over ethernet |
| Camera body dimensions | 86mm wide x 80mm deep x 90mm high |
| Camera weight, including ringlight | 1.25 lb. (0.57 kg |
| Number of camera mount points | 5 |
| **RINGLIGHT** | |
| Strobe Type | Near Infrared (750 nm), Full Infrared (850 nm) |
| Strobe electronics | Integrated, software reprogrammable |
| LEDs | 36 surface mount |
| Adjustable Illumination | Yes |
| **ENVIRONMENTAL** | |
| Temperature, Operating | 10° to 25°C, (50° to 77°F) |

| | |
|---|---|
| Temperature, Storage | -40° to 65°C (-40° to 149°F) |
| Relative Humidity | 20% to 80% (non-condensing) |
| **SYSTEM CONNECTIVITY** | |
| Plug and play compatibility | Yes |
| System connectivity | Gigabit Ethernet |
| Custom control interface | Yes |
| Camera number indicator | Yes |
| Integrated camera display panel | No |
| Insight auto-focus | Yes |
| Communication status indicators | Yes |
| Maximum number of cameras | Unlimited |
| Multiple camera types in system | Yes |
| Genlock to external video source | Yes |
| Synchronize to external signa | Yes |
| IP addressable | Yes |
| IP reconfigurable | Yes |
| External A/D sync and clock | Yes |

### 9.1.7 Video Projectors

***Optoma HD144X (Optoma Corporation, New Taipei City, Taiwan)***

Table 15. Technical Specifications of Optoma's HD144X projector

| | |
|---|---|
| **Display/Image** | |
| Display technology | DLP |
| Resolution | 1080p Full HD (1920x1080) |
| Brightness | 3,400 lumens |
| Contrast ratio | 23,000:1 |
| Native aspect ratio | 16:9 |
| Aspect ratio - compatible | 4:3 |
| Keystone correction - vertical | 40 |
| Uniformity | 80% |
| Screen size | 0.71m - 7.65m (28in - 301in)(Diagonal) |
| **Lamp Info** | |
| Light source | Lamp |
| Lamp watts | 240 |
| Lamp life (hours) | 3500 (Bright), 12000 (Dynamic), 10000 (Eco) |
| **Optical** | |
| Throw ratio | 1.47:1 - 1.62:1 |
| Projection distance (m) | 1m - 9.8m |
| Zoom | 1.1 |
| Zoom type | Manual |
| Focal length (mm) | 15.59 ~ 17.14 |
| Native offset | 116% |
| **Connectivity** | |
| Connections | **Inputs** 1 x HDMI 1.4a 3D support + MHL, 1 x HDMI 1.4a 3D support |

| | |
|---|---|
| | **Outputs** 1 x Audio 3.5mm, 1 x USB-A power 1.5A **Control** 1 x 3D sync, 1 x 12V trigger |
| **General** | |
| Noise level (typical) | 25dB |
| PC compatibility | FHD, UXGA, SXGA, WXGA, HD, XGA, SVGA, VGA, Mac |
| 2D compatibility | NTSC M/J, 3.58MHz, 4.43MHz PAL B/D/G/H/I/M/N, 4,43MHz SECAM B/D/G/K/K1/L, 4.25/4.4MHz 480i/p, 576i/p, 720p(50/60Hz), 1080i(50/60Hz), 1080p(50/60Hz) |
| 3D compatibility | Side-by-Side:1080i50 / 60, 720p50 / 60 Frame-pack: 1080p24, 720p50 / 60 Over-Under: 1080p24, 720p50 / 60 |
| 3D | Full 3D |
| Security | Security bar, Kensington Lock, Password protected interface |
| OSD / display languages | 25 languages: Arabic, Czech, Danish, Dutch, English, Farsi, Finnish, French, German, Greek, Hungarian, Indonesian, Italian, Japanese, Norwegian, Polish, Portuguese, Romanian, Russian, Chinese (simplified), Spanish, Swedish, Chinese (traditional), Turkish, Vietnamese |
| Operating conditions | 5°C ~ 40°C, Max. Humidity 85%, Max. Altitude 3000m |
| Remote control | Backlit home remote |
| Speaker count | 1 |
| Watts per speaker | 10W |
| **Power** | |
| Power supply | 100 ~ 240V, 50 ~ 60Hz |
| Power consumption (standby) | 0.5W |
| Power consumption (min) | 205W |
| Power consumption (max) | 295W |
| **Weight and Dimensions** | |
| Net weight | 2.87kg |
| Dimensions (W x D x H) (mm) | 316 x 244 x 108 |

### *Epson EH-TW5650 (Epson, Suwa, Nagano Prefecture, Japan)*

Table 16. Technical Specifications of Epson's EH-TW5650 projector.

| | |
|---|---|
| **Technology** | |
| Projection System | 3LCD Technology, RGB liquid crystal shutter |
| LCD Panel | 0.61 inch with MLA (D10) |
| **Image** | |
| Colour Light Output | 2,500 Lumen- 1,650 Lumen (economy) in accordance with IDMS15.4 |
| White Light Output | 2,500 Lumen - 1,650 Lumen (economy) in accordance with ISO 21118:2012 |
| Resolution | Full HD 1080p, 1920 x 1080, 16:9 |

| | |
|---|---|
| High Definition | Full HD 3D |
| Aspect Ratio | 16:9 |
| Contrast Ratio | 60,000 : 1 |
| Light source | Lamp |
| Lamp | UHE, 200 W, 4,500 h durability, 7,500 h durability (economy mode) |
| Keystone Correction | Auto vertical: ± 30 °, Manual horizontal ± 30 ° |
| Colour Processing | 10 Bits |
| 2D Vertical Refresh Rate | 192 Hz - 240 Hz |
| 3D Vertical Refresh Rate | 400 Hz - 480 Hz |
| Colour Reproduction | upto 1.07 billion colours |
| **Optical** | |
| Projection Ratio | 1.33 - 2.16:1 |
| Zoom | Manual, Factor: 1.6 |
| Lens | Optical |
| Lens Shift | Manual |
| Image Size | 30 inches - 300 inches |
| Projection Distance Wide/Tele | 2.35 m - 3.82 m ( 80 inch screen) |
| Projection Lens F Number | 1.51 - 1.99 |
| Focal Distance | 18.2 mm - 29.2 mm |
| Focus | Manual |
| Offset | 10 : 1 |
| **Connectivity** | |
| Interfaces | VGA in, HDMI in (2x), MHL, USB 2.0 Type A, USB 2.0 Type B (Service Only), Stereo mini jack audio out, Wireless LAN IEEE 802.11b/g/n, Miracast |
| Epson iProjection App | Ad-Hoc / Infrastructure |
| **Advanced Features** | |
| Security | Kensington lock, Security cable hole, Wireless LAN security |
| 3D | Active |
| 2D Colour Modes | Dynamic, Natural, Cinema, Bright Cinema |
| 3D Colour Modes | 3D Dynamic, 3D Cinema |
| 3D Supported formats | Side by side, Top and bottom |
| Features | 3D depth adjustment, Built-in speaker, Epson Super White, Frame interpolation, Horizontal and vertical keystone correction, MHL audio/video interface, Quick Corner, Screen Mirroring, Split-Screen-Function, Wireless LAN capable, iProjection App |
| Video Colour Modes | Cinema, Dynamic, Natural, Bright Cinema |
| **General** | |
| Energy Use | 296 Watt, 227 Watt (economy), 0.2 Watt (standby), On mode power consumption as defined in JBMS-84 256 Watt |
| Supply Voltage | AC 100 V - 240 V, 50 Hz - 60 Hz |

| | |
|---|---|
| Product dimensions | 309 x 285 x 122 mm (Width x Depth x Height) |
| Product weight | 3.5 kg |
| Noise Level | Normal: 37 dB (A) - Economy: 27 dB (A) |
| Temperature | Operation 5° C - 35° C, Storage -10° C - 60° C |
| Humidity | Operation 20% - 80%, Storage 10% - 90% |
| Options | 3D active shutter glasses, Air filter |
| Loudspeaker | 10 Watt |
| Colour | White |

### 9.1.8 Rehabilitation Devices

***Rehawalk® (zebris Medical GmbH, Isny im Allgäu, GE)***

Table 17. Technical Specifications of zebris' Rehawalk®.

| **Model** | mercury med | quasar med | locomotion 150/50 med | locomotion 190/65 med |
|---|---|---|---|---|
| Speed | • 0 - 10 km/h<br>• 0 - 22 km/h | 0 - 25 km/h | 0 - 10 km/h | 0 - 25 km/h |
| Running surface | 150 x 50 cm | 170 x 65 cm | 150 x 50 cm | 190 x 65 cm |
| Elevation | 0 -25 % | 0 - 28 % | 0 - 25 % | 0 - 25 % |
| Sensor surface | • 112x49 cm<br>• 108x47 cm | • 132x56 cm<br>• 135x54 cm | • 112x49 cm<br>• 108x47 cm | • 162x54 cm<br>• 162x56 cm |
| Number of sensors | • 3432<br>• 7168 | • 4576<br>• 10240 | • 3432<br>• 7168 | • 5632<br>• 12288 |
| Motor | 3.3 kW | | | |
| Max. user weight | 200 kg | | | |
| Track access height | 18 - 23 cm | | | |
| Color | pure-white | | | |
| Sampling frequency | 120 Hz | | | |
| Measuring range | 1-120 Nm² | | | |
| PC interface | USB | | | |

## 9.2 Game Design: Hardware Devices – Technical Specifications

### 9.2.1 Desktops

***Apple iMac (2017)***

Table 18. Technical Specifications of Apple's iMac (2017)

| **Model** | 21.5-inch | 27-inch |
|---|---|---|
| Display | - 21.5-inch (diagonal) LED-backlit display. 1920-by-1080 resolution with support for millions of colors.<br>- 21.5-inch (diagonal) Retina 4K display. 4096-by-2304 resolution with support for one billion colors 500 nits brightness Wide color (P3) | 27-inch (diagonal) Retina 5K display. 5120-by-2880 resolution with support for one billion colors. 500 nits brightness Wide color (P3) |

| | | |
|---|---|---|
| Processor | - 2.3GHz dual-core Intel Core i5 (Turbo Boost up to 3.6GHz)<br>- 3.0GHz quad-core Intel Core i5 (Turbo Boost up to 3.5GHz)<br>- 3.4GHz quad-core Intel Core i5 (Turbo Boost up to 3.8GHz) | - 3.4GHz quad-core Intel Core i5 (Turbo Boost up to 3.8GHz)<br>- 3.5GHz quad-core Intel Core i5 (Turbo Boost up to 4.1GHz)<br>- 3.8GHz quad-core Intel Core i5 (Turbo Boost up to 4.2GHz) |
| Memory | - 8GB of 2133MHz DDR4 memory<br>- 8GB of 2400MHz DDR4 memory | 8GB (two 4GB) of 2400MHz DDR4 memory; four SO-DIMM slots, user accessible |
| Storage | - 1TB (5400-rpm) hard drive<br>- 1TB Fusion Drive | - 1TB Fusion Drive<br>- 2TB Fusion Drive |
| Graphics | - Intel Iris Plus Graphics 640<br>- Radeon Pro 555 with 2GB of VRAM<br>- Radeon Pro 560 with 4GB of VRAM | - Radeon Pro 570 with 4GB of VRAM<br>- Radeon Pro 575 with 4GB of VRAM<br>- Radeon Pro 580 with 8GB of VRAM |
| Video Support and Camera | - FaceTime HD camera:<br>Simultaneously supports full native resolution on the built-in display at millions of colors (21.5-inch) or 1 billion colors (21.5-inch 4K) and:<br>One 5120-by-2880 (5K) external display at 60Hz with support for 1 billion colors, or<br>Two 3840-by-2160 (4K UHD) external displays at 60Hz with support for 1 billion colors, or<br>Two 4096-by-2304 (4K) external displays at 60Hz with support for millions of colors<br>- Thunderbolt 3 digital video output:<br>Native DisplayPort output over USB-C.<br>Thunderbolt 2, HDMI, DVI, and VGA output supported using adapters | - FaceTime HD camera<br>Simultaneously supports full native resolution on the built-in display at 1 billion colors and:<br>One 5120-by-2880 (5K) external display at 60Hz with support for 1 billion colors, or<br>Two 3840-by-2160 (4K UHD) external displays at 60Hz with support for 1 billion colors, or<br>Two 4096-by-2304 (4K) external displays at 60Hz with support for millions of colors<br>- Thunderbolt 3 digital video output Native DisplayPort output over USB-C Thunderbolt 2, HDMI, DVI, and VGA output supported using adapters (sold separately) |
| Audio | - Stereo speakers<br>- Microphone<br>- 3.5 mm headphone jack (Support for Apple iPhone headset with microphone) | |
| Connections and Expansion | - 3.5 mm headphone jack<br>- SDXC card slot<br>- Four USB 3 ports (compatible with USB 2)<br>- Two Thunderbolt 3 (USB-C) ports with support for: DisplayPort, Thunderbolt (up to 40 Gbps), USB 3.1 Gen 2 (up to 10 Gbps), Thunderbolt 2, HDMI, DVI, and VGA supported using adapters<br>- 10/100/1000BASE-T Gigabit Ethernet (RJ-45 connector)<br>- Kensington lock slot | |
| Input | - Magic Keyboard<br>- Magic Keyboard with Numeric Keypad<br>- Magic Mouse 2<br>- Magic Trackpad 2 | |
| Wireless | - 802.11ac Wi-Fi wireless networking IEEE 802.11a/b/g/n compatible | |

| | | |
|---|---|---|
| | - Bluetooth 4.2 wireless technology | |
| Size and Weight | Height: 17.7 inches (45.0 cm)<br><br>Width: 20.8 inches (52.8 cm)<br><br>Stand depth: 6.9 inches (17.5 cm)<br><br>Weight: 12.5 pounds (5.66 kg)2 | Height: 20.3 inches (51.6 cm)<br><br>Width: 25.6 inches (65.0 cm)<br><br>Stand depth: 8 inches (20.3 cm)<br><br>Weight: 20.8 pounds (9.44 kg)2 |
| Electrical and Operating Requirements | Line voltage: 100–240V AC<br>Frequency: 50Hz to 60Hz, single phase<br>Operating temperature: 50° to 95° F (10° to 35° C)<br>Relative humidity: 5% to 95% noncondensing<br>Operating altitude: tested up to 10,000 feet | |
| Operating System | macOS | |

### *Dell XPS Tower Special Edition*

Table 19. Technical Specifications of Dell's XPS Tower Special Edition

| | |
|---|---|
| CPU | 8th Generation Intel® Core™ i7-8700K 6-Core Processor (12MB Cache, up to 4.7 GHz) |
| Graphics | NVIDIA® GeForce® GTX 1070 with 8GB GDDR5 Graphics Memory |
| RAM | 16GB, DDR4, 2666MHz |
| Power Supply | 460W |
| Storage | M.2 256GB PCIe x4 SSD + 2TB 7200 rpm Hard Drive |
| Optical drive | Tray Load DVD-RW Drive (Reads and Writes to DVD/CD) |
| Ports | Front: 1x USB 3.1 Type-C, 3x USB 3.1 Gen 1 Ports, 1x Mic-in, 1x Headphone, 1x SD Card Reader (SD, SDHC, SDXC)<br><br>Rear: 3x USB 3.1 Gen 1 ports, 1x USB 3.1 port<br>2x USB 2.0 ports, 1x USB 3.1 Type-C port<br>1x HDMI, 1x Display Port, 1x Gigabit Ethernet, 1x Audio ports (5.1 channel (3 Jack) |
| Slots | Up to 4 total 3 HDD/1 SSD; ODD<br>4x PCIe expansion slots (x1, x1, x4, x16)<br>4x DIMM slots (supports up to 64GB) |
| Chassis | Bays: 3x Hard Disk Drive bays, 1x Optical Disk Drive bay<br><br>Chipset: Z370 with Intel K CPUs only (some features of Z chipset not supported, including dual graphics)<br><br>Color Options: Black<br><br>Exterior Chassis Materials: Molded plastic / Sheet Metal |
| Wireless | 802.11ac + Bluetooth 4.2, Dual Band 2.4&5 GHz, 1x1 |
| Operating system | Windows 10 Home 64bit English |
| Weight | 22 pounds (10kg) |
| Dimensions | Height: 15.22" (386.5mm) x Width: 7.09" (180mm) x Depth 14.02" |

(356mm)
Starting weight: 22lbs (10Kg)

### 9.2.2 Smartphones

#### *Samsung Galaxy S9/S9 Plus*

Table 20. Technical Specifications of Samsung's Galaxy S9/S9 Plus

| **Model** | Galaxy S9 | Galaxy S9+ |
|---|---|---|
| Dimensions | 147.7 mm × 68.7 mm × 8.5 mm (5.81 in × 2.70 in × 0.33 in) | 158.1 mm × 73.8 mm × 8.5 mm (6.22 in × 2.91 in × 0.33 in) |
| Weight | 163 g (5.7 oz) | 189 g (6.7 oz) |
| Operating system | Samsung Experience 9.0 on top of Android 8.0 "Oreo" | |
| System on chip | Exynos 9810 | |
| CPU | Exynos: Octa-core (4×2.7 GHz & 4×1.7 GHz)<br>Snapdragon: Octa-core (4×2.8 GHz & 4×1.7 GHz) Kryo 385 | |
| GPU | Exynos: Mali-G72 MP18<br>Snapdragon: Adreno 630 | |
| Memory | 4 GB LPDDR4X RAM | 6 GB LPDDR4X RAM |
| Storage | 64, 128 or 256 GB UFS 2.1 | 64, 128 or 256 GB UFS 2.1 |
| Removable storage | microSD, expandable up to 512 GB | |
| Battery | Non-removable, 3000 mAh | Non-removable, 3500 mAh |
| Data inputs | Sensors: Accelerometer, Barometer, Fingerprint scanner (rear-mounted), Iris scanner, Geomagnetic sensor,<br>Gyroscope, Hall sensor, Proximity sensor, Heart Rate and Blood Pressure sensor<br>Other: Physical sound volume keys, Bixby key | |
| Display | 2960×1440 1440p Super AMOLED capacitive touchscreen Infinity Display<br>Gorilla Glass 5<br>5.8 in (150 mm), 570 ppi | 2960×1440 1440p Super AMOLED capacitive touchscreen Infinity Display<br>Gorilla Glass 5<br>6.2 in (160 mm), 529 ppi |
| Rear camera | 12 MP (1.4 μm, f/1.5/2.4), OIS, 4K at 30 or 60 fps (limited to 5 min), QHD at 30 fps, 1080p at 30 or 60 fps, 720p at 30 and slow motion at 960 fps | Dual 12 MP (1.4 μm, f/1.5/2.4) + 12 MP ((1.0 μm), f/2.4), Dual OIS, 4K at 30 or 60 fps (limited to 5 min), QHD at 30 fps, 1080p at 30 or 60 fps, 720p at 30 fps and slow motion at 960 fps |
| Front camera | 8 MP (1.22 μm, f/1.7), autofocus | |
| Sound | Stereo speakers tuned by AKG, Dolby Atmos surround sound | |
| Connectivity | Wi-Fi 802.11 a/b/g/n/ac (2.4/5GHz), VHT80, MU-MIMO, 1024-QAM Bluetooth 5.0 (LE up to 2Mbps), ANT+, USB-C, 3.5mm headphone jack, NFC, location (GPS, Galileo, GLONASS, BeiDou) | |

### *iPhone XS / iPhone XS Max*

Table 21. Technical Specifications of Apple's iPhone XS / iPhone XS Max

| **Model** | iPhone XS | iPhone XS Max |
|---|---|---|
| Dimensions | H: 143.6 mm (5.65 in)<br>W: 70.9 mm (2.79 in)<br>D: 7.7 mm (0.30 in) | H: 157.5 mm (6.20 in)<br>W: 77.4 mm (3.05 in)<br>D: 7.7 mm (0.30 in) |
| Weight | 177 g (6.2 oz) | 208 g (7.3 oz) |
| Operating system | Original: iOS 12.0<br>Current: iOS 12.1, released October 30, 2018 | |
| System on chip | Apple A12 Bionic | |
| CPU | 2.49 GHz hexa-core 64-bit | |
| Modem | Intel PMB9955 (XMM7560) | |
| Memory | 4 GB | |
| Storage | 64, 256 or 512 GB | |
| Removable storage | None | |
| Battery | 3.81 V 10.13 W·h (2658 mA·h) Li-ion | 3.80 V 12.08 W·h (3174 mA·h) Li-ion |
| Display | 5.8 in (150 mm), 2436x1125 px<br><br>458 ppi, Super Retina HD: AMOLED, 625 cd/m² max. brightness (typical), with dual-ion exchange-strengthened glass, and 3D Touch | 6.5 in (170 mm), 2688×1242 px<br><br>458 ppi, Super Retina HD: AMOLED, 625 cd/m² max. brightness (typical), with dual-ion exchange-strengthened glass, and 3D Touch |
| Sound | Stereo speakers | |
| Other | IP68 IEC standard 60529 (splash, water, and dust resistant), Qi wireless charging, USB-C to Lightning (connector) fast charging | |
| Hearing aid compatibility | M3, T4 | |

## 9.2.3 Tablets

### *iPad Pro*

Table 22. Technical Specifications of Apple's iPad Pro

| **Model** | 12.9-inch | 11-inch |
|---|---|---|
| Initial operating system | iOS 12.1 | |
| SoC | Apple A12X Bionic | |
| Motion coprocessor | Apple M12 | |
| CPU | 7nm, Octa-core SOC; 4x Vortex performance cores + 4x Tempest efficiency cores | |
| GPU | 7-core GPU | |
| Display | 12.9 inches (330 mm) [diagonal] Liquid Retina Display, True Tone display with ProMotion display<br><br>2732-by-2048 pixel resolution at 264 ppi | 11 inches (280 mm) [diagonal] Liquid Retina Display, True Tone display with ProMotion display<br><br>2388-by-1668 pixel resolution at 264 ppi |

| | | |
|---|---|---|
| | (Retina Display) | (Retina Display) |
| Wireless | Wi-Fi (802.11a/b/g/n/ac); dual channel (2.4 GHz and 5 GHz); HT80 with MIMO<br>Bluetooth 5.0 technology | |
| Environmental sensors | Accelerometer<br>Gyroscope<br>Ambient light sensor<br>Face ID<br>Barometer | |
| Dimensions | 280.6 mm (11.05 in) (h)<br>214.9 mm (8.46 in) (w)<br>5.9 mm (0.23 in) (d) | 247.6 mm (9.75 in) (h)<br>178.5 mm (7.03 in) (w)<br>5.9 mm (0.23 in) (d) |
| Weight | Wi-Fi: 631 g (1.391 lb)<br>Wi-Fi + Cellular 633 g (1.396 lb) | 468 g (1.032 lb) |
| Connectors | USB-C<br>Apple Smart Connector | |

### *Samsung Galaxy Tab S3*

Table 23. Technical Specifications of Samsung's Galaxy Tab S3

| | |
|---|---|
| Operating system | Android 7.0 "Nougat" (Upgradeable to Android 8.0 "Oreo") |
| System-on-chip | Qualcomm MSM8996 Snapdragon 820 |
| CPU | Quad-core (2x2.15 GHz Kryo + 2x1.6 GHz Kryo) |
| Memory | 4 GB LPDDR4 |
| Storage | 32 GB (can add up to 256GB MicroSD Card) UFS 2.0 |
| Display | 2048×1536 px (QXGA) Super AMOLED display (264 ppi),<br>9.7 in (25 cm) diagonal |
| Graphics | Adreno 530 |
| Sound | Four built-in stereo speakers tuned by AKG |
| Input | Multi-touch screen, fingerprint scanner, digital compass, proximity and ambient light sensors, accelerometer |
| Camera | 13 MP AF rear-facing camera with LED flash, 5 MP front-facing camera |
| Connectivity | Wi-Fi 802.11a/b/g/n/ac (2.4 & 5GHz), Bluetooth 4.2<br>4G & WiFi model: 4G/LTE, GPS |
| Power | 6,000 mAh battery |
| Dimensions | 237.3 mm (9.34 in) H<br>169.0 mm (6.65 in) W<br>6.0 mm (0.24 in) D |
| Weight | 429 g (0.946 lb) (Wi-Fi); 434 g (0.957 lb) (LTE) |

### 9.2.4 Augmented Reality Smartglasses

*Microsoft HoloLens*

Table 24. Technical Specifications of Microsoft's HoloLens

| | |
|---|---|
| Optics | See-through holographic lenses (waveguides)<br>2 HD 16:9 light engines<br>Automatic pupillary distance calibration<br>Holographic Resolution: 2.3M total light points<br>Holographic Density: >2.5k radiants (light points per radian) |
| Operating system and Apps | Windows 10<br>Windows Store<br>Holograms<br>Microsoft Edge<br>Photos<br>Settings<br>Windows Feedback<br>Calibration<br>Learn Gestures |
| Processor | Custom Microsoft Holographic Processing Unit HPU 1.0,<br>Intel 32-bit (1GHz) with TPM 2.0 support |
| Memory | 2 GB RAM<br>1 GB HPU RAM |
| Storage | 64 GB (flash memory) |
| Display | See-through holographic lenses (waveguides)<br>2x HD 16:9 light engines<br>Automatic pupillary distance calibration<br>2.3M total light points holographic resolution, 2.5k light points per radian |
| Sound | Spatial sound technology<br>External speakers, 3.5mm audio jack |
| Sensors | 1x Inertial measurement unit (accelerometer, gyroscope, and magnetometer),<br>4x environment understanding cameras,<br>1x mixed reality capture,<br>4x microphones, ambient light sensor<br>1x depth camera |
| Controller | Gestural commands via sensors and HPU |
| Camera | 1x 2MP photo / HD video camera |
| Connectivity | IEEE 802.11ac<br>Bluetooth 4.1 LE<br>Micro-USB 2.0 |
| Platform | Windows 10 |
| Weight | 579 g (1.28 lb) |
| Power | 2-3 hour active use battery life, 2 weeks standby, passive cooling (no fans), |

| | |
|---|---|
| | Fully functional when charging |
| Human Understanding | Spatial sound<br>Gaze tracking<br>Gesture input<br>Voice support |

### Magic Leap One

Table 25. Technical Specifications of Magic Leap One

| Lightpack | |
|---|---|
| CPU | NVIDIA® Parker SOC; 2 Denver 2.0 64-bit cores + 4 ARM Cortex A57 64-bit cores (2 A57's and 1 Denver accessible to applications) |
| GPU | NVIDIA Pascal™, 256 CUDA cores; Graphic APIs: OpenGL 4.5, Vulkan, OpenGL ES 3.3+ |
| RAM | 8 GB |
| Storage Capacity | 128 GB (actual available storage capacity 95GB) |
| Power | Built-in rechargeable lithium-ion battery. Up to 3 hours continuous use. Battery life can vary based on use cases. Power level will be sustained when connected to an AC outlet. 45-watt USB-C Power Delivery (PD) charger |
| Connectivity | Bluetooth 4.2, WiFi 802.11ac/b/g/n, USB-C |
| Lightwear | |
| Audio Input | Voice (speech to text) + real world audio (ambient) |
| Audio Output | Onboard speakers and 3.5mm jack with audio spatialization processing |
| Control | |
| Haptics | LRA Haptic Device |
| Tracking | 6DoF (position and orientation) |
| Trackpad | Touch sensitive |
| LEDs | 12-LED (RGB) ring with diffuser |
| Power | Built-in rechargeable lithium-ion battery. Up to 7.5 hours continuous use. 15-watt USB-C charger |
| Other inputs | 8-bit resolution Trigger Button; Digital Bumper Button; Digital Home Button |

### Moverio BT-300 Smart Glasses

Table 26. Technical Specifications of Moverio's BT-300 Smart Glasses

| Wearable Device Details: | |
|---|---|
| Model Type: | Si-OLED (Silicon-Organic Light-Emitting Diode) |

| | |
|---|---|
| Power Supply Voltage Controller: | 5 V/900 mA via Micro USB terminal |
| Battery Life: | Approx. 6 hours |
| Weight Headset: | 2.5 oz / 69 g (excluding cable) |
| Power Supply Voltage AC Adapter: | 100 – 240 V AC ±10%, 50/60 Hz with Micro USB cable |
| Battery Type: | Li-Polymer |
| Dimensions Headset: | 7.52" x 7.01" x 0.98" (W x D x H) |
| Dimensions Controller: | 2.20" x 4.57" x 0.91" (W x D x H) |
| Weight Controller: | 4.55 oz / 129 g |
| Optical | |
| Driving Method: | Mono Crystalline Silicon Active Matrix |
| Display Size: | 0.43"-wide panel (16:9) |
| Pixel Number: | 921,600 pixels (1280 RGB x 720) |
| Refresh Rate: | 30 Hz |
| Field of View: | 23 degrees (diagonal) |
| Screen Size - Projected Distance: | 40" at 2.5 m – 320" at 20 m |
| Color Reproduction: | 24-bit color (16.77 million colors) |
| General: | |
| Operating Systems: | Android 5.1 |
| Humidity: | 20% – 80% |
| Operating Temperature: | 41 °F to 95 °F (5 °C to 35 °C) |
| Sensors | |
| Camera | 5 Megapixel |
| GPS | Yes, in Controller |
| Compass | Yes, 3-axis in both Headset and Controller |
| Gyroscope | Yes, 3-axis in both Headset and Controller |
| Accelerometer | Yes, 3-axis in both Headset and Controller |
| Android Platform: | |
| Pre-installed Applications: | Browser, Calculator, Calendar, Camera, Clock, Contacts, Downloads, Email, Music, Search, Settings, Sound Recorder, Moverio Apps Market, MovFiler |
| Connectivity Wearables: | |
| Wireless LAN: | IEEE 802.11a/b/g/n/ac with Wi-Fi CERTIFIED™, Miracast® (source/sink) ODFM, DS-SS |
| Bluetooth | Bluetooth Smart Ready Class2 (2.5 mW, 10 m), V4.1 support profile: HSP/A2DP/HID/OPP/SPP/AVRCP/PAN |
| CPU & Memory: | |
| CPU | Intel Atom x5 1.44GHz Quad Core |
| Internal Memory: | Approx. 16GB (including Android OS) |
| RAM | 2GB |
| User Interface: | |
| Function Key: | Power, Home, Recents, Back, Function (Lock, Brightness, 2D/3D), Volume (+/-) |
| Touch-pad Pointing Method: | Capacitive Multi-Touch |
| Supported File Formats: | |

| | |
|---|---|
| Supported File Formats: | Picture: JPEG, PNG, BMP, GIF |
| Video | MP4 (MPEG4/H.264+AAC), MPEG2 (H.264+AAC), VP8 |
| Audio | WAV, MP3, AAC |
| 3D Supports: | Side-by-side |

### Meta 2 Development Kit

Table 27. Technical Specifications of Meta 2 Development Kit

| | |
|---|---|
| Platform | Windows, Mac OS |
| Resolution | 2560 x 1440 |
| Refresh Rate | 60 Hz |
| Field of View | 90-degree field of view |
| Tracking | 6DOF |
| Rotational Tracking | IMUs |
| Audio | 4 speaker near-ear audio system |
| Camera | 720p front-facing camera |
| Sensors | Sensor array for hand interactions and positional tracking |
| Connectivity | 9-foot cable for video, data, and power (HDMI Version 1.4b) |
| Recommended PC Requirements | |
| Graphics | NVIDIA GTX 960 / AMD R9 280 |
| CPU | Intel Core i7 (desktop CPU) |
| Memory | 8GB RAM |
| Game Engine | 64-bit Unity 5.3x |
| Storage | 10GB |
| Video | HDMI 1.4b |
| Sound Card | Intel HD-compatible sound card |
| USB Ports | USB 3.0 |
| OS | Windows 10 64-bit or newer |