GINSODA – A Research Software Tool to Develop and Study Evaluation Criteria for Physiotherapeutic Exercises Based on Plantar Pressure Distribution

L. Strunz[1], P. Wesberg[1], M. Walter-Hubberten[2] und J. Villwock[1]

[1]Berliner Hochschule für Technik, Luxemburger Str. 10, 13353 Berlin

[2] trinitas GmbH, Brandenburger Str. 37, 14542 Werder (Havel)

Abstract

This paper presents the current state of the Get Insole Data (GINSODA) project, which is dedicated to the creation of a research software tool. It processes data from insoles equipped with several types of sensors. GINSODA will enable researchers to implement and test different criteria to evaluate physiotherapeutic exercises based on raw data. In addition to data analysis, the tool offers live visualization for direct feedback that might provide a benefit to the training progression and health of the patients.

Software which is distributed with the insoles for analyzing insole data usually provides predefined reports. In contrast, GINSODA software is designed with modularity in mind to allow easy customization, extension, and data exchange. This aims to fit the needs of research. The software architecture is outlined, and it is described how the platform enables the development and validation of new criteria.

An initial use case is conducted to develop criteria for evaluating a physiotherapeutic exercise by analyzing plantar pressure. This exercise aims to improve the posture and stability while standing and should enhance classical therapy of patients with back pathologies. The physiological reasoning behind the importance and mechanics of the foot is given, the proposed criterion and its implementation is presented.

To find parameters for the implementation of the analysis criterion resulted in a preliminary study. This showed unexpected distributions in the raw data, e.g., differences in the total weight compared to the selected software calibration value. This inspired another study, that compares the pressure data both spatially and with regards to its temporal behavior to a platform-based sensor system.

The paper concludes with an outlook into the future of the GINSODA project.

Keywords*:* Research Software Tool, Sensor Insoles, Plantar Pressure Distribution, Physiotherapeutic Exercise

1 Introduction

Back pain is one of the most common types of musculoskeletal conditions in Germany with 25% of women and 17% of men experiencing chronical back pain [1, p. 69]. In Berlin back pain is accounting for more than 20% of all days off work [2, p. 31]. Chen et al. concluded that lower back pain is "a major public health issue globally". He claims that "[i]ncreasing population awareness about its risk factors and preventive measures […] are needed to reduce the future burden of this condition". [3, p. 1] Despite its prevalence, there are gaps in knowledge about risk factors and prevention. The quality of physical activity is insufficiently recorded in the studies, although physical fitness is a protective factor according to prevailing opinion [4, p. 15].

Recent findings indicate that the widespread "nonspecific" back pain can be treated by improving posture. In addition to strong leg and trunk muscles, good sensorimotor control is important for stabilizing the trunk and postural control. [4, pp. 45–47] In patients with back pain, postural control appears to be impaired, in part due to altered sensory inputs and offsets in sensory reference values for specific movement patterns [4, p. 53]. The coupling mechanisms between the spine, pelvis and extremities are significant for dysfunctions of the human musculoskeletal system and hereby for back pain. Significant for spinal stability are the muscle chains[1]. These extend across the back to the pelvis and into the legs and actively stabilize mutual interaction. The longitudinal chain of the leg ends in the feet via the tendons of the lower leg muscles. [4, pp. 38–45] In conjunction with the short foot muscles, they stabilize the plantar vault.

GINSODA tries to contribute to preventive measures by allowing researcher to augmenting physiotherapeutic exercises based on the patient's plantar pressure distribution. GINSODA will enable researchers to implement criteria for evaluating exercises and offers live visualization capabilities to augment the patient's training. The first exercise to be evaluated with GINSODA aims to prevent and rehabilitate back pain by improving postural control and stability through reactivating muscles holding the plantar vault.

GINSODA provides a framework to implement and evaluate new criteria, by providing a pipeline that handles, transforms, analyses, visualizes, and stores data. Hence, it allows researchers to validate the concept of augmentation as well as individual criterion for specific exercises in user studies. This leads the way to applications that have the potential to increase the quality of training and help patients to avoid errors in training and therapy.

[1] Functional coupling of multiple muscle-fascia-tendon units in a concatenated arrangement.

Plantar pressure sensor systems are available as insoles to wear in-shoe or as platforms on the floor. In general, the use of insoles is motivated by the fact that they are easily portable, relatively cheap and can be used during in- and outdoor sports or daily activities. However, plates are often regarded as the gold-standard, due to better measurement accuracy and resolution [5]–[7]. However, both enable software applications for the evaluation of pressure distribution in sports, rehabilitation or biomechanics by researchers, therapists, and patients.

The development of GINSODA is rooted in the BMBF-funded projects BewARe [8] (sensor-supported movement training for seniors in an intelligent augmented reality system) and VITALAB [9][10] (living labs for laboratory and field studies to evaluate virtual technologies for a healthy life). The BewARe project is motivated by the fact that regular physical activity has a great preventive effect on good health and well-being and has a positive influence on chronic diseases. Therefore, a sensor-supported movement training is being designed in an intelligent AR system to playfully motivate people to engage in health-promoting activities in personalized training programs. Based on motion capturing the execution of the exercise is evaluated and feedback supports patients to improve the movement. The VITALAB.Mobile is a mobile laboratory for testing digital health applications in a truck. In the future, the VITALAB.Mobile should also reach rural regions and be used where there are no dedicated laboratories for advanced digital technologies.

2 Software Engineering

This section will discuss the software engineering that has been done to develop the GINSODA research software tool. In the chosen approach of agile software development, newly discovered requirements can be easily incorporated, and solutions improved. While not all aspects should be listed here, the following aspects where of essence for the development:

- Small incremental steps (with version control),
- Prioritization of feature development by the team,
- Refactoring and testing integrated in development cycles.

The following subsections will first discuss the use cases and requirements GINSODA satisfies so far. Secondly, the hard- and software architecture is outlined. Finally, some general remarks about the implementation, the reasoning behind some technical decisions and details about the expendability of the code base is discussed.

2.1 Use Cases and Requirements

The objective of GINSODA is to be a software tool, that enables researchers to easily implement new evaluation criteria for physiotherapeutic exercises based on plantar pressure distribution. Thereby, the main use cases of GINSODA are Live Visualization, Data Playback and Batch Mode. While the first two are geared towards using the software with a patient, the last one focuses on the development of new criteria.

Live Visualization	Augment training session by providing live feedback in tests and user studies
Data Playback	Visualize criteria based on stored raw data
Batch Mode	Allow external automation/optimization software to use GINSODA's analysis as a process

The most important requirements are:

- User-friendly:
  - The app is usable by an instructed person, that is not a computer expert.
  - The app provides a visually pleasing Graphical User Interface.
- Raw data import from stream (UDP) or file.
- GINSODA provides interfaces for data analysis or optimization:
  - Configuration in-/exportable.
  - Output data in machine parse able file format.
  - Batchable analysis pipeline.
- Include filter to reduce signal noise in the input.
- Errors are logged.
- Code is tested.
- Live visualization of the current data, i.e., an input through the sensor has an immediate response in the visualization.

2.2 Hard- and Software Architecture

GINSODA is designed as group of individual programs that can be run as individual processes, namely: main, client, fake server, and app. This is the first layer of modularity of the GINSODA tool. GINSODA's architecture in the Live Visualization use case is depicted in Figure 1.

The figure also illustrates the sensor data pipeline of Moticon sensor insole SCIENCE, which was chosen for the first application prototype: The data is sent from the soles to an Android mobile via Bluetooth, that relays the data over a (wireless) local area network to a desktop pc, where the Moticon Desktop App is used to relay the data as UDP[2] packages.

[2] User Datagram Protocol, a transport layer protocol

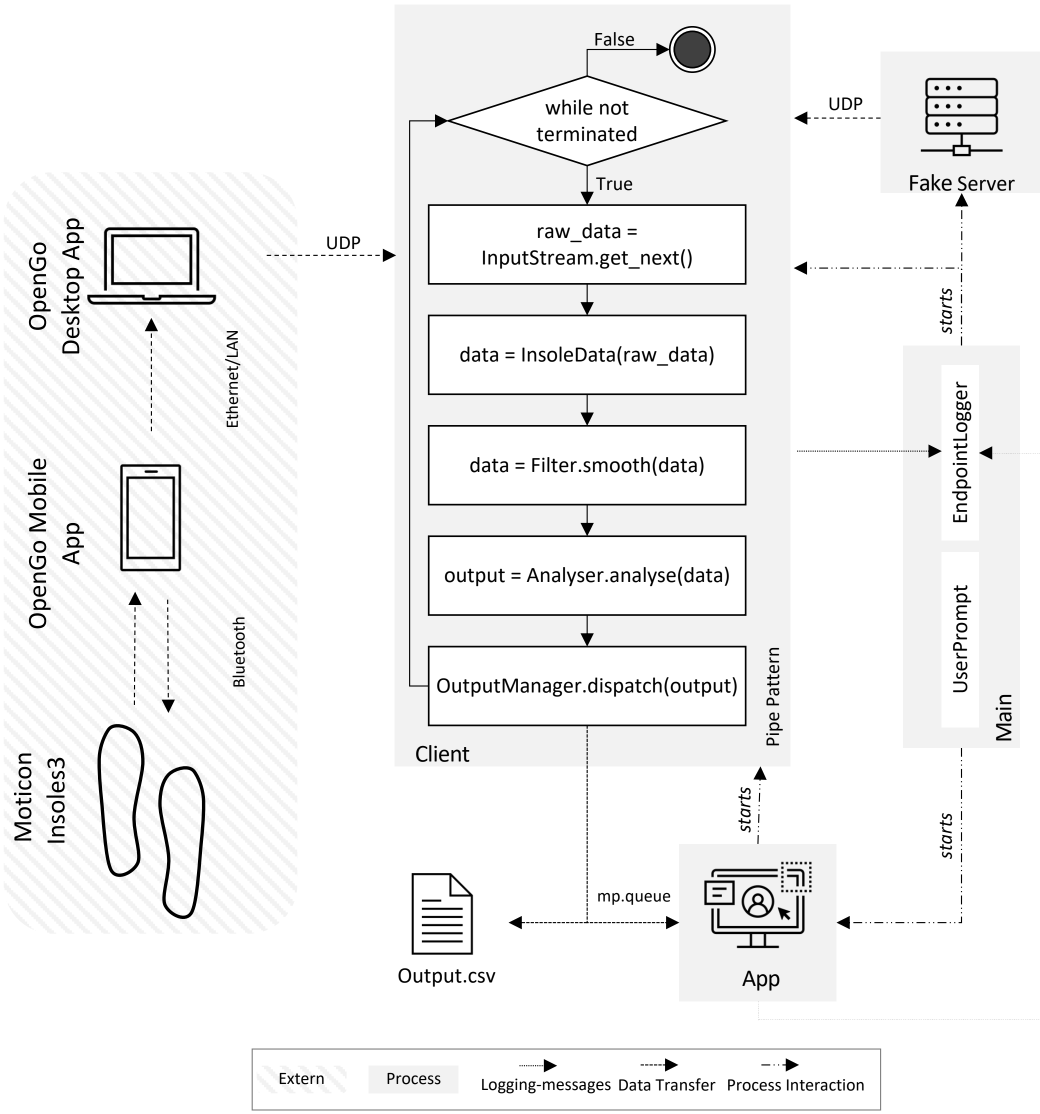

Figure 1: Hard- and Software Structure of GINSODA for Live Visualization

The GINSODA main provides the user with a minimal terminal-based user interface to spawn processes that the user might want to request. Further, it houses the logging endpoint, that is needed for multiprocessing logging. The main enables a non-development user to start the GINSODA software tool conveniently with a double click on a batch script from the file explorer.

The GINSODA client is based on the well-known pipe and filter architecture pattern [11, p. 182ff]. It either consumes individual UDP packages or can be configured to process data from an input file. The InputStream.get_next() method gets data from the configured source, decodes it, if necessary and returns the data, which is parsed into a GINSODA specific data structure. In the next step a configurable smoothing filter can be applied to the input. This can be either be a simple or a weighted moving average, with configurable window size and weights. After that, the results according to the configured analysis methods are stored in a new data structure by the analyzer. Finally, the output manager calls the configured methods that should be called to distribute or store the data.

The GINSODA App provides the user with a graphical user interface (GUI) that is hosted in the browser. The App focuses on the graphical visualization of the pressure data analysis results. Additionally, the app provides an interface to change the configuration and the user can start and stop the client process from the GUI. A multiprocessing queue is used for data exchange between the client and the app processes.

The last process is the fake server, which is primary used as a development tool, to fake the behavior of the Moticon desktop app. This allows for automated system testing between an extern UDP data source and the client.

2.3 Implementation and Technical Decisions

The Software is built as a Python[3] project. It relies on some common modules in the scientific and data analysis communities such as NumPy[4], Pandas[5], Plotly[6] Graphing Libraries and Plotly Dash. The last two allow the fast creation of interactive and scientific graphics within a common web browser, that are visually pleasing. Plotly Dash was chosen as the GUI framework together with the Plotly Graphing Libraries since an attempt to use TKinter[7] (a regular Python GUI framework) in an exploring development cycle seemed to be more tedious and less elegant. Although Plotly Dash is not really made to visualize data at high refresh rates (> 1 Hz), the performance of its current implementation is deemed good enough at around 6 Hz for live visualization.

A mayor concern was to encapsulate individual parts of the tool. Therefore, client and app are completely separated into different processes. A multiprocessing queue is used to define an interface through which the data is transported from the client to the app. Hence, changing the approach regarding the GUI and visualization should be easier than with a deeper integration. This design decision introduced the need for network-based logging, which is implemented by wrapping Python's logging module.

[3] https://www.python.org: multi-purpose programming language, used version 3.7
[4] https://numpy.org/: python package for scientific computing
[5] https://pandas.pydata.org/: python package data analysis
[6] https://plotly.com/: python packages for interactive visualization and web app
[7] https://docs.python.org/3.7/library/tkinter.html: GUI tool, that is distributed with python

One mayor task is to implement the analysis and visualization to be configurable, i.e., that the user can select which method(s) are used. This is accomplished by implementing a parameter listing the requested analysis tasks by name as a string. A helper method wrapping python's getattr is than utilized to return a specific implementation. Therefore, the configuration of the GINSODA tool is stored in a single yaml[8] file. It can easily be edited with a text editor or from the configuration page of the GINSODA web app. Yaml was selected due to its very clean and easily readable syntax, especially compared to xml or json.

With regards to testing, it was decided to focus on the core functionality of the project which is data processing. Hence, the dash app and the visualization are not part of the automated test regime yet and must be checked manually.

3 Muscular Controlled Standing

This chapter introduces and explains the concept and importance of *muscular controlled standing* by discussing the biomechanics and anatomy of the foot and its importance in physiological training. A criterion to evaluate *muscular controlled standing* is proposed and its implementation is discussed. Furthermore, a physiotherapeutic exercise is suggested to consciously train the activation of the muscles.

3.1 Physiological Fundamentals

3.1.1 The Foot

In its bipedal position the human body is an inherently unstable structure. With only a small area of support base compared to the height of the body's center of gravity, the body must be balanced and stabilized permanently. [12, p. 266] The complex biomechanical functions of the foot are an important prerequisite for an upright posture in standing, walking, or running. The correspondingly complex anatomy of the foot and its sensorimotor control are the basis for stability and mobility.

The Foot's skeleton consists of 26 bones and is divided into three sections: the Tarsus (heel), Metatarsus (middle) and Digiti (toes) [13, pp. 216–227]. The bones are connected to each other by joints called Articulationes Pedis. Figure 2 shows the foot bones forming the three arches in a physiological neutral position. Together, the arches create the plantar vault of the foot. Two arches are located at the medial (A–C) and lateral (B–C) sides. The third arch is in the distal part of the Metatarsus (A–B). The structure and biomechanical importance is described in chapter 3.1.4. [14, pp. 282–292]

[8] https://www.yaml.org: human readable data serialization language

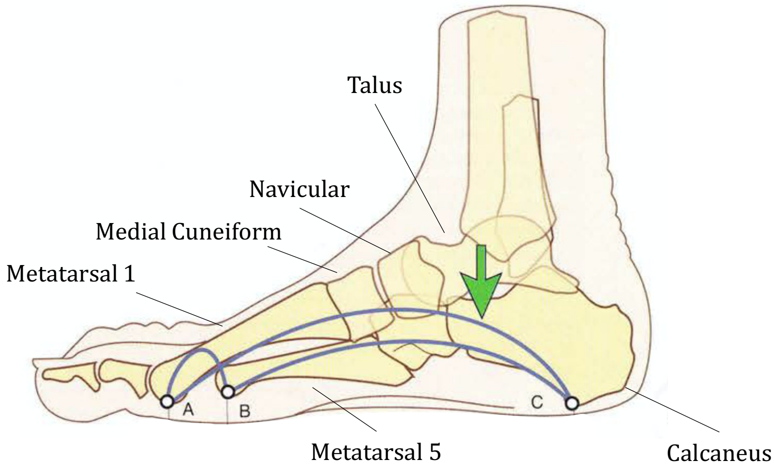

Figure 2: Medial Arch Adapted from [12, p. 235] Fig. 5

All joints of the foot are connected and stabilized to each other by capsules and numerous ligaments. In addition, these structures provide damping due to their viscoelastic properties and support of the foot's arches when loaded. The muscles–tendon units are crucial for stabilizing and maintaining the planar vault under sustained loads. [13, pp. 228–241] [12, p. 236]

3.1.2 Neuroanatomy of the Foot

Precise muscular control is required to ensure the functionality of the foot. The contraction of the muscles is controlled by motor nerves, which originate in the central nervous system (brainstem, cerebellum, and cerebrum). The centrally stimulated activation of muscles is based on numerous sensory inputs. In addition to the receptors of the surface (skin organ), it is the proprioceptors of the locomotor system that provide the necessary signals to ensure an appropriate motor response. Different proprioceptors provide sensory information about muscle-tendon tension, muscle length or joint angle. [15, pp. 191–213]

The neuromusculoskeletal system has the ability to regulate certain deviations form centrally determined motions in a self-stabilizing manner. On the lowest level, perturbations in length and especially contractile velocity cause immediate changes in the contractile force. This intrinsic properties of muscle is coined *preflexes* by [16]. On the level of the spinal cord, the spinal reflex arcs, which connect receptors through the spinal cord to the muscle actuators, allow for further self-stabilization. The system of pre- and reflexes trigger a cascading adaption of muscle activation which stabilizes the body's posture in case of deviations (e.g. a perturbation of the balance).

At the highest level, the brain is the adaptive controller for any locomotor task. [15, pp. 201–202], [17, pp. 1–12]

3.1.3 Biomechanics of the Plantar Vault

The anatomical structure of the foot (chapter 3.1.1) creates three arches and thus the plantar vault. The musculoskeletal structure and its mechanical properties allow for deviations in the shape, also of the arches. [12, pp. 232–241] Thus allow the foot to adapt to uneven ground and dampen the forces acting on it. [12, pp. 242–253]

The three support points are located at the distal caput of the Os Metatarsal I (A) and Os Metatarsal V (B) and at the Processus medialis et lateralis tuberis of the Calcaneus (C), see Figure 3 as reference. The transversal arch, which is the shortest and shallowest, spans between A and B. The longest and most accentuated arch is the medial arch, connecting A and B. Its keystone, the Os Naviculare, is ~1.5-2 cm over the ground. The lateral arch between B and C is shorter and less pronounced as the medial arch (~0.3-0.5 cm over ground at Os Cuboideum), with the Anterior Calcaneal Process as keystone. [12, pp. 234–241][14, pp. 337–344]

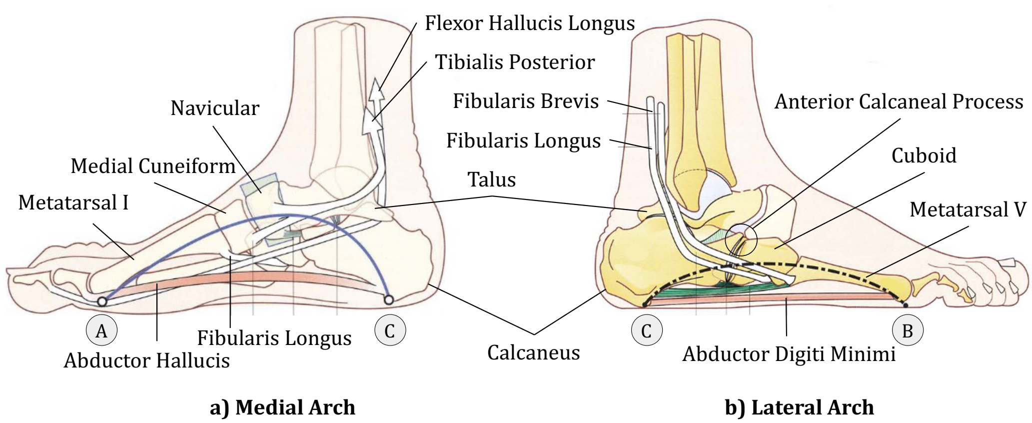

Figure 3: Medial and Lateral Arches Adapted from [12, pp. 237, 239] Fig. 7 and 18

The muscles are the only elements in the foot that can be activated voluntarily and therefore are the means of performing *active standing*. The muscles supporting the arches can basically be divided into long muscles (connected to the lower leg) and short muscles (in the foot). Figure 3 and Figure 4 show some of the key muscles of the foot that are crucial to the stability of the plantar arch. The short muscles collectively brace the arches that form the plantar vault, by tensioning a single arch or the connection of multiple arches. The long muscles primarily tension the longitudinal arches in the foot: The medial arch is primarily supported by the Tibialis Posterior muscle, the Peroneus Longus muscle (not shown), the Flexor Hallucis Longus and the

Abductor Hallucis as shown in Figure 3a. The lateral arch, as shown in Figure 3b, is mainly braced by the Peroneus Longus et Brevis and the Abductor Digiti Minimi muscles. The transverse arch is secured by the Abductor Hallucis, Posterior Tibialis, Peroneus Longus and the Abductor Digiti Minimi muscles, see Figure 4. [12, pp. 234–240], [13, pp. 268–287], [14, pp. 329–336]

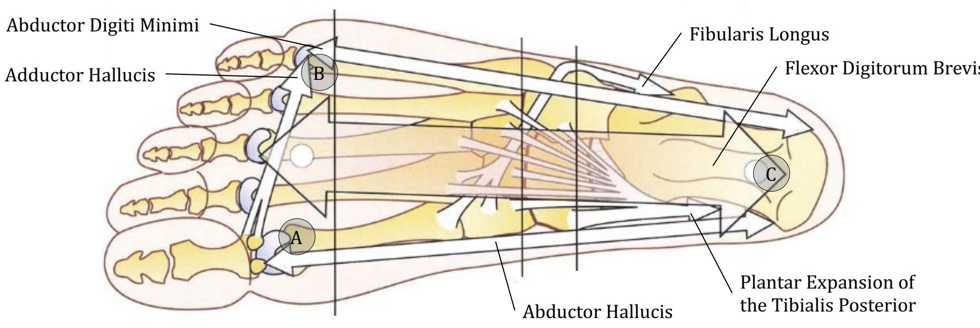

Figure 4: Plantar Vault Top View Adapted from [12, p. 241] Fig. 28

The Talus transfers the vertical load from the body to the plantar vault, in which the load is distributed through the arches towards the three support points, see Figure 2. An ideal distribution of the load is approx. 50% at support C, 30% and 20% at the supports A and B, respectively. In different sources, like Kapandji [12, p. 242] or Hochschild [14, p. 344], slightly different values can be found. Also not all sources specify the type of stance (bipedal or one-legged), and therefore the relation might differ.

The arches and therefore the plantar vault is passively guaranteed by the bones, capsules, and ligaments. Under sustained load, it would widen and gradually collapse. To maintain the vault and its function, active muscles are crucial. Furthermore, the coordinated interplay of the muscles provides stability of the structure and thereby ensures orderly locomotion. [12, pp. 234–241], [18, p. 61]

3.2 Implementation of the *Force Triangle* Criterion

From the literature an ideal force distribution between the three supporting points of the Plantar Vault is known: heel: 50 %, lateral: 20 %, medial: 30 % (see chapter 3.1.3). This is used as the foundation of a new criterion, named *Force Triangle*. The *Force Triangle* criterion evaluates the execution of the exercise described in chapter 3.3. The implementation of a new criterion in the GINSODA tool includes an analysis method (chapter 3.2.1) and at least one visualization (chapter 3.2.2).

3.2.1 Implementation of the Analysis Method

Common sensor systems, insoles as well as platforms, capture the pressure distribution by many sensors. The single sensors are arranged in a specific order, depending to the sensor system. The first implementation of the *Force Triangle* analyses the pressure data from Moticon sensor insole SCIENCE, containing 16 single pressure sensors as shown in Figure 5.

To compute the force distribution between the support points, the code implements the following equation:

$$d_i = \frac{\sum_{k=1}^{16} f_k \, w_{i,k}}{\sum_{i=1}^{3} \sum_{k=1}^{16} f_k \, w_{i,k}} . \tag{1}$$

d_i denotes the percentage of the weighted force applied to the *i*-th corner of the triangle in relation to the total weighted force. k indexes a sensor position. f refers to the force and w to the weight associated to that sensor position. The weighting is a mathematical construct and can theoretically be chosen arbitrarily. The weight $w_{i,k}$ is introduced, so it is possible to include a value in two corners or disregard it in the analysis. The individual weights can be chosen in the configuration file. Different approaches of selecting the weights in Eq. (1) could be conceivable. Consequently, the values of d are a distribution, but for arbitrary weights this is not the distribution of the reaction force at the support in relation to the total force applied to the foot since the denominator might not be the total force. To ensure a physically reasonable choice of the weights, one can introduce the following constrain:

$$\sum_{i=1}^{3} w_{i,k} = 1 \; \forall \, k \quad \text{and} \; w_{i,k} \; \geq \; 0 \; \forall \, i, k \, . \tag{2}$$

With this constrain, the denominator is the total force measured and the individual weights $w_{i,k}$ are between 0 and 1. The initial approach to determining the weights, presented in Figure 5, combines this constrain with the geometrically nearest and the physically reasonable support point. Note that the sensor reading of field 11 was split equally between the two supports on the forefoot, since it seems to be between them.

1 – heel (C) $w_i = 1$ for $i \in [1,2,3,4,5,6]$

2 – lateral (B) $w_i = 1$ for $i \in [8,12,13,16]$, $w_{11} = 0.5$

3 – medial (A) $w_i = 1$ for $i \in [7,9,10,14,15]$, $w_{11} = 0.5$

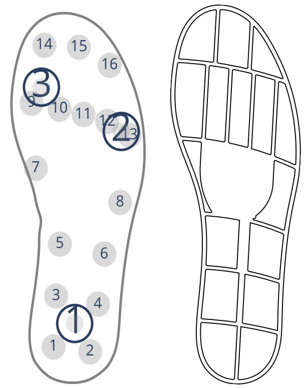

Figure 5: Weights, Sensor Numbering and Support Points, Sensor Outline [19, p. 4]

An alternative approach is based on the idea, that a well-trained person can demonstrate a correct repetition. From this idea the following steps are planned to arrive at a set of weights:

1. A trained person performs the exercise correctly multiple times.
2. The pressure data of repetitions is averaged in time and these averages are averaged over the repetitions to provide an *ideal* pressure distribution.
3. The weights, that will result in the ideal *Force Triangle* are calculated based on the average distribution, i.e. by optimization algorithms.
4. Finally, conducting a sensitivity study with the standard deviation of the time averaged fields, to be able to assess the optimized weighting.

3.2.2 Implementation of the Visualization

The GINSODA supports two different types of visualization: visualizing the current data point (LiveVisualizer) or visualizing the data from the last x seconds (HistoryVisualizer). The visualization is based around a public show method, that calls the configured methods for each specific criterion. To visualize a criterion a create and an update method must be implemented.

The live visualization of the *Force Triangle* aims to present the patient with a clear reference regarding the difference to the ideal values at the support points, as shown in Figure 2. The create method plots a graph, showing the sole's outlines, the individual sensor positions within the sole[9] and marks the support positions. The combination of outline and support position gives a clear spatial reference. While performing the exercise, the update method adjusts the color code and scale of the overlay, as in Figure 6. The red and green color mapping scheme provides direct

[9] This can be turned off and on from the configuration.

binary feedback, whether the patient is in the configured tolerances around the ideal distribution value at the given support. Additionally, the scaling provides additional feedback on how large the deviation is in comparison to the set values.

With this setup an interactive environment is created by the GINSODA software tool for the patient, that lets the patient train their muscle-controlled stand by consciously controlling the muscles in their lower limb to accomplish a 'all green' feedback.

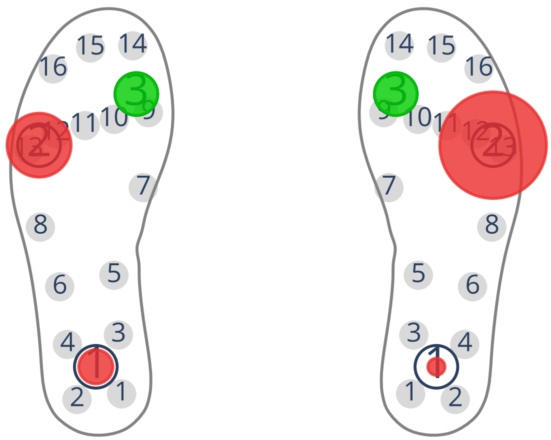

Figure 6: Force Triangle Graphic on Update

The history visualization shows the data over time as a line plot, which is primarily aimed towards the therapeutic interest. The visualization is shown in Figure 7. The individual data points are highlighted on the line as markers. The set ideal values are shown in the same color. A configurable time window is shown to the user.

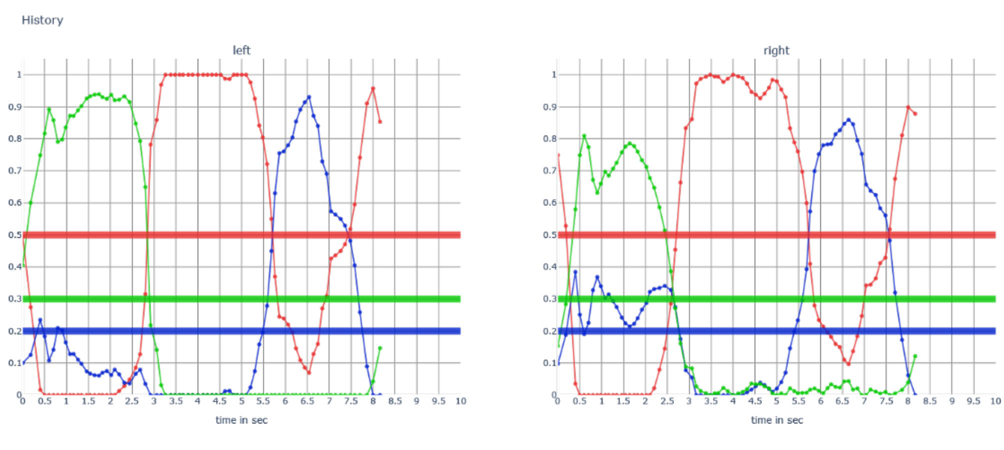

Figure 7: Force Triangle Sequence Graphic

3.3 Definition of the Training Exercise

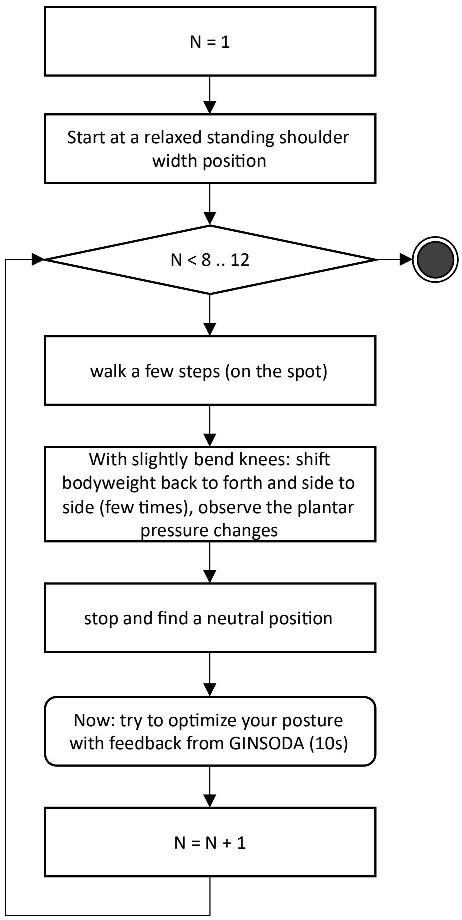

Figure 8: Exercise Algorithm

The exercise is targeted for patients that exhibit orthopedic indications of spine/back issues. Typical approaches focus on back exercises that are not performed in an upright standing position. For a more holistic approach to back pathologies, it is assumed that training the bases of the body, i.e., the lower leg and especially the feet, could be beneficial. From the biomechanical perspective, it is important that the foots muscles actively supports the plantar vault, which is what the exercise is supposed to train. Hence, the main goal of the exercise is to reactivate the sensor motoric functionality of the lower leg/foot. This is where the app developed within GINSODA supports patients with feedback on their plantar pressure distribution.

One training set is depicted as an algorithm to the left in Figure 8. One to three sets could be integrated into a training session. If the training is supervised by a trainer, he might give additional feedback regarding the bodies posture.

4 Preliminary Study – Weighting Optimization

There are different approaches of weighting the sensor reading in the analysis of pressure distribution. As proposed in chapter 3.2.1, they can be optimized to result in the expected force distribution based on an ideal execution of the exercise. This is feasible only if a trained person performs the exercise multiple times replicating similar pressure distributions. To verify this hypothesis the raw pressure data is analyzed in two steps: First, the sensor readings for each repetition are averaged over time. Then, the distribution of the averaged sensor readings between the repetitions is analyzed. Ideally, normal distributions with relatively small standard deviation should be observed for both.

It is assumed that a *good* result shows a distribution of lightly loaded sensors has a range of two to three sensor divisions[10] (.5 to .75 N/cm^2), while the acceptable range for highly loaded sensors is assumed to be 4 to 6 sensor divisions (1 to 1.5 N/cm^2). For a standing person, pressure peaks of about 10 N/cm^2 can be expected as high, while low is up to 2 N/cm^2. The reference for the range are the whiskers of the boxplot, hence excluding outliers.

Subsequently, the design of the study, the results, and the discussion of the results will be discussed in this chapter.

4.1 Study Design

A sport therapist (male, 28 years, 181cm, 74kg) was selected to perform the exercise outlined in chapter 3.3 twenty times. The Moticon SCIENCE Sensor Insole (model Insole3, size6: EU42/43) was used with the currently newest firmware (as of the 4th of March 2022) and the OpenGo Apps (Android: 03.10.00(80); Windows: 03.05.00) to collect the data. The shoes used (UnderArmour Mojo M – EU42.5) do not provide additional support to the plantar vaults. The insoles were worn 15 min to warm up and then calibrated from the OpenGo Android App to the participants weights. The insoles were configured to sample at 100Hz and to use the strict automatic zeroing mode provided by Moticon. Due to the selected zeroing mode the participant had to walk a few steps, before the selected zeroing mode allowed for the next data recording.

The execution of the exercise was captured on video as well. The video was later imported into the OpenGo Desktop App, where it was automatically synchronized by the OpenGo Software. The participant was instructed to clench his fists loosely, while he feels he performs the exercise correctly. This visual reference then was used to crop the data, as shown in Figure 9. The data then was exported as an txt file.

[10] sensor division of the Moticon Insole3 is .25 N/cm^2

Figure 9: Cropping of the Data within the OpenGo Software

4.2 Results

The data is analyzed and visualized in boxplots (linear quartile method) that shows median (solid), mean (dotted), quartiles and whiskers of the distribution. The criterion for outliers is 1.5 times the interquartile range. Additionally, the scatter plot shows the individual datapoints. This method was chosen since the purpose was an explorative data analysis.

The pressure data over time of a representative repetition is shown in Figure 10. The division of the sensors (.25 N/cm^2) produce groups in the scatter plot of the measured values. The interquartile range is between 0.25 and 0.75 N/cm^2 while the ranges from 0.5 to 2.75 N/cm^2. In the trend, the higher the average pressure, the wider the distribution.

In Figure 10, 4 sensors can be identified that exclude specific values: left 14, right 6, right 8 and right 13. This result in voids which can be found in the data of these sensors in many other repetitions as well.

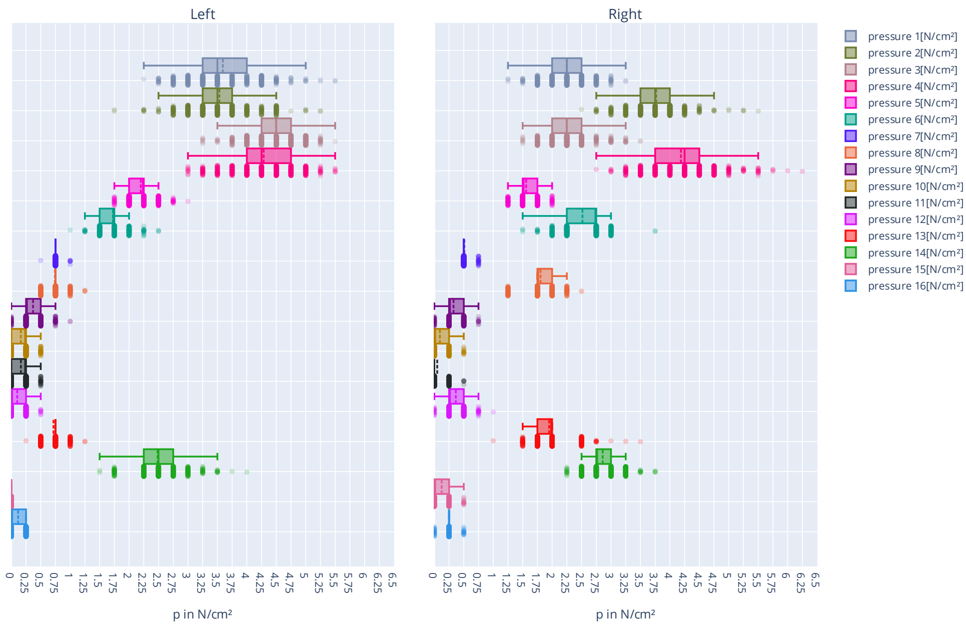

Figure 10: Distribution of Pressure Data over Time of a Representative Repetition

Of particular interest is whether the repetitions give a similar mean pressure distribution. Therefore, the temporal mean values are analyzed and plotted in Figure 11. For many sensors the distribution of temporal means is significantly larger than the division of the sensor system (.25 N/cm^2). Especially the highly loaded sensors at the backfoot (Sensors 1 to 4) show a very wide variety, e.g., sensor 2 (left: 1.1 to 5.1 N/cm^2, right: .9 to 5.8 N/cm^2). Some distributions are skewed to the mean/median, e.g., sensors 10 and 11 or the sensors 2 and 3 of the left insole. This would not be case for normally distributed values. Sensor 6 of the right sole exhibits a grouping of three clusters (at the whiskers and the mean/median values).

Both Figure 10 and Figure 11 show that the data of many sensors produce long whiskers compared to the interquartile range. Sensors with larger ranges of pressure data over time also show larger scatter of temporal means, e.g., sensors 1 to 6, 11 (right) and 12.

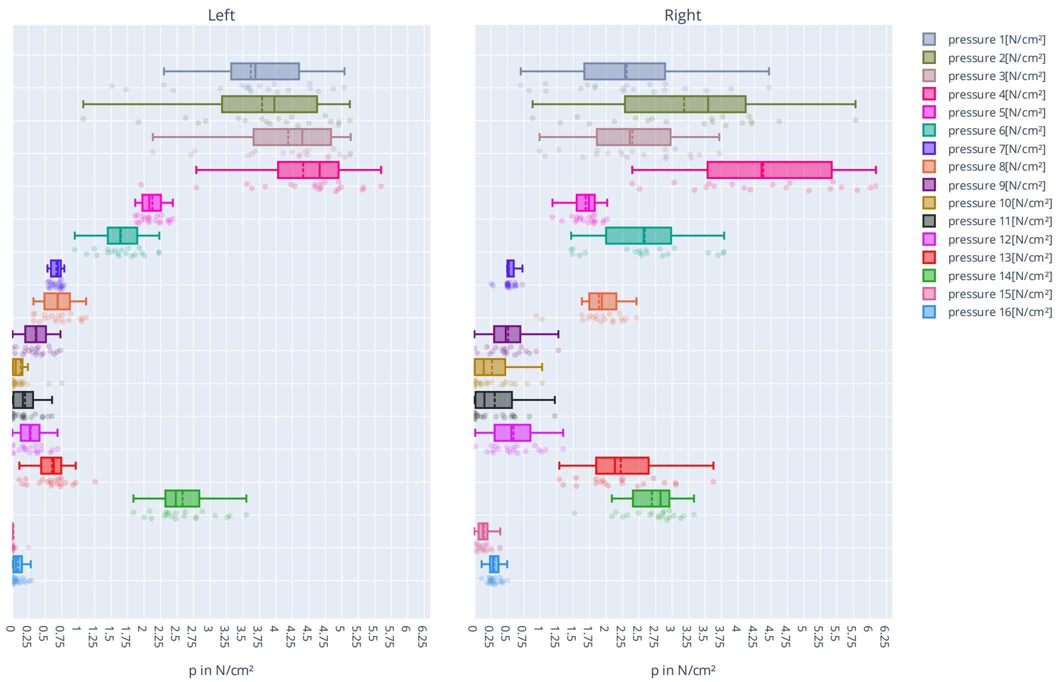

Figure 11: Distribution of the Temporal Averages of the Pressure Distribution

It was noticed that the total forces detected by the insoles seemed to be quite low in the relevant timespan, see Figure 9: 638N or 65kg. Hence, the relative error of the time averaged total weight detected by the insoles compared to the value that was used to calibrate the insoles via the OpenGo app (74kg) is plotted in Figure 12.

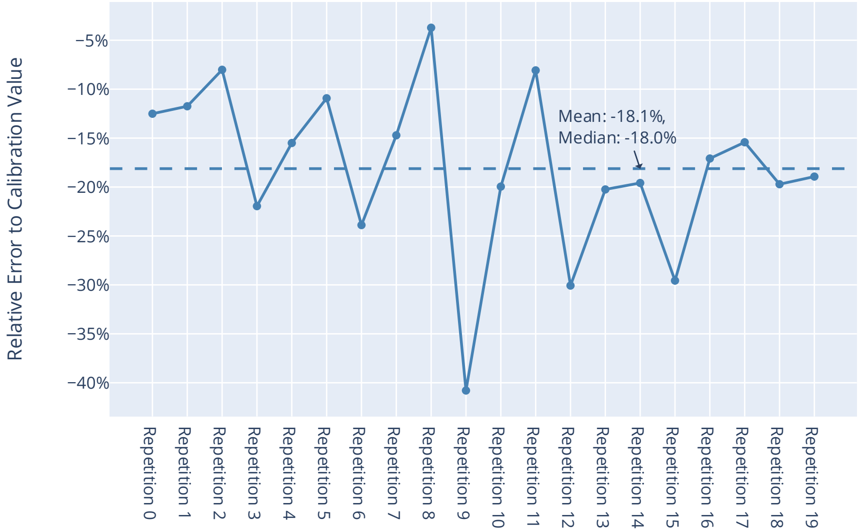

Figure 12: Relative Error Detected Weight to Calibration Weight

The relative error in Figure 12 shows significant deviations: All detected values are significantly too small and range from approx. 4 % to 42 %, which relates to an absolute error of appr. 40 kg. Both the mean and median values are located at around 18 % deviation.

4.2 Discussion

With regards to the individual repetition, distribution was assumed to be smaller. Minor variations in the pressure values due to compensating movements during the exercise were assumed to be smaller than 1 N/cm^2. Therefore, it is suspected that the Moticon SCIENCE sensor insoles tend to introduce significant noise. The results of temporal mean values (Figure 11) demonstration skewedness, high width of the distribution and some grouping of values. Noteworthy, the grouping seen for sensor right 6 might correlate to the voids of this sensor readings (Figure 10). The relative error between the detected weight and the calibration value is deemed very high with a mean of 18 % and because all errors are negative a systematic error seems to be at play. The results implicate that the sensors are not suitable for the intended application to analyze the Force Triangle as discussed in chapter 3.2.1.

5 Study – Comparison of Two Sensor Systems

Due to the results of the preliminary study, it was concluded that the sensor system may not be suitable for the intended application, i.e., augment therapeutic exercises which lead to quasi static loads. So, another study is conducted to evaluate whether the Moticon sensor system might not be the correct choice. Hence, the static behavior of the sensor system is tested and compared to another sensor system, namely the Zebris FDM plantar pressure plate. The chapter introduces the design of the study, presents the results, and concludes by discussing them.

5.1 Study Design

The general idea for this study was to compare the mean value spatially and the distribution of values over time.

Table 1: Factors and setting for full factorial design of experiment

Load Type	Sole Side	Sole Size
Static 14.7 kg, Foam	Left | Right	Size4 | Size6
Static 14.7 kg, Sandbag	Left | Right	Size4 | Size6
Human 70.8 kg, supported one legged stand	Left | Right	Size4 | Size6

Table 1 provides an overview of the tested combinations to create a wider variety of loading conditions to comparison between the sensor systems. For each combination three measurements of approx. 10 s where conducted. Two sensor sole sizes and three types of loading where selected. The left and right sole where individually loaded, bringing the total number of 36 measurements.

To load both sensor systems as equally as possible, the Moticon insole was placed on top of the Zebris plate for all loading types as shown in Figure 13. To avoid high stress gradients to the sensor due to edge pressure, two different more compliant constructions are used. One uses two pads cut from a firm foam. Another uses sandbags to create 3 distinct load areas representing the Force Triangle and result in higher pressure gradients with same total weight applied. Both loading types avoid the thicker middle area of the sole due to the battery compartment. The third load type is a human standing one legged directly on the sole. The balance is supported by both hands, that were placed on fixed structures in the proximity, enabling an almost static stance.

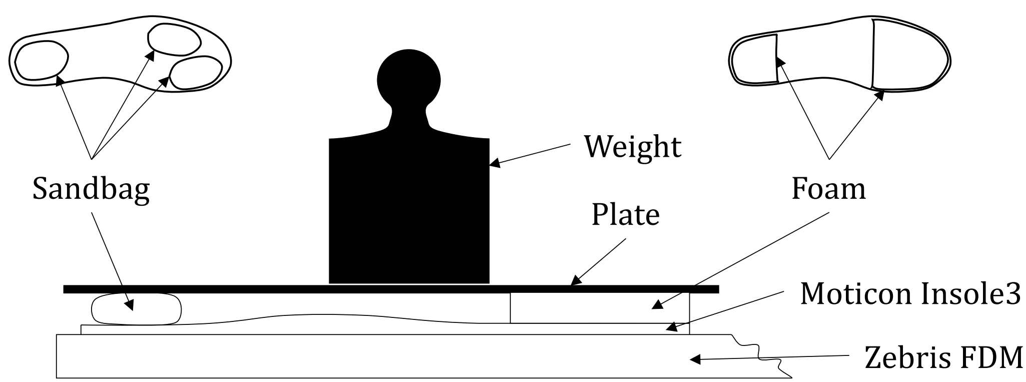

Figure 13: Measurement Configuration for Static Load

Both measurement systems were configured to 100 Hz and manually zeroed before each measurement. Both systems were started at the same moment be hand. While in the Zebris software a measurement time of ten seconds was predefined, the Moticon system was stopped manually. The Moticon system was used without the software calibration, since the soles were not used inside a shoe and the software calibration would need active inputs by a wearer, which obviously was impractical for the static weight.

A grid representing individual sensors in the Zebris plate was plotted and sticked into place as reference. To be able to compare the data spatially, the sole was then positioned on the plate closely aligned with the longitudinal axis [20, p. 5], shown in Figure 14. This allows to define spatial offsets in the analysis.

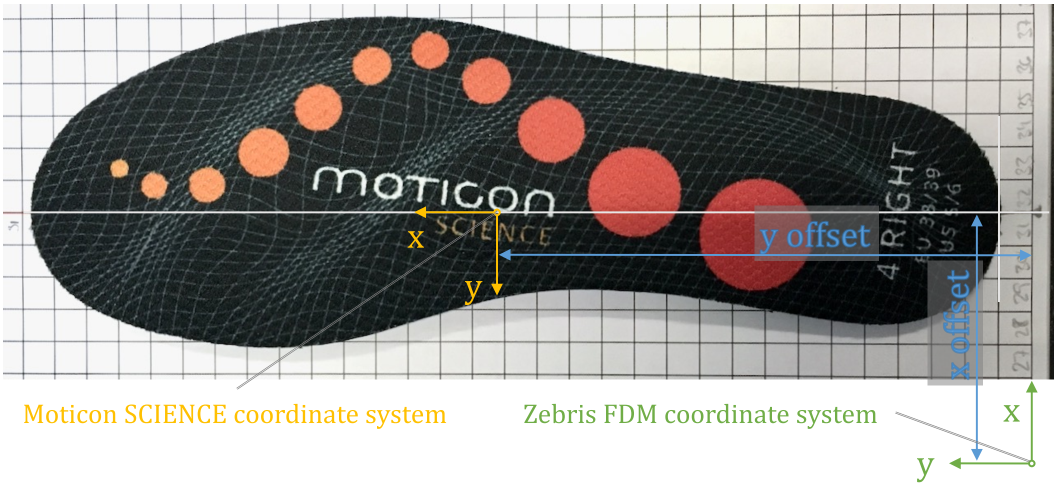

Figure 14: Moticon Insole Right Size4 Positioned on the Zebris FDM Plate[11].

5.2 Results

5.2.1 Time Averaged Spatial Comparison

For spatial comparison, the raw pressure data from both sensor systems are interpolated onto a common grid. The Zebris data with a density of 1.4 sensors/cm^2 is linearly interpolated. The Moticon data is interpolated by the nearest neighbor approach using the sensor center location [20, p. 7] since there are only 16 individual values. The pressure difference is defined as:

$$\Delta\tilde{p}_i = \tilde{p}_{i,Moticon} - \tilde{p}_{i,Zebris} \quad (3)$$

$\tilde{p}_\mathrm{i}$ is the interpolated pressure at the interpolation point i.

Three examples of the left insole size 4 were selected from measurements to present the individual comparison. All graphs can be found at (https://labor.bht-berlin.de/cae/forschung-und-drittmittelprojekte/ginsoda).

In the center of Figures 15-17, the time-averaged difference in pressure distribution of insole to plate is plotted. To the left-hand side the sensor outline is provided, based on the Moticon Documentation [19, p. 4]. In the Figures 15 and 16 the picture to the right-hand side shows the position of the foam pads or the sandbags respectively.

[11] Not to scale. Zebris starts indexing its sensors at the lower left corner of the plate.

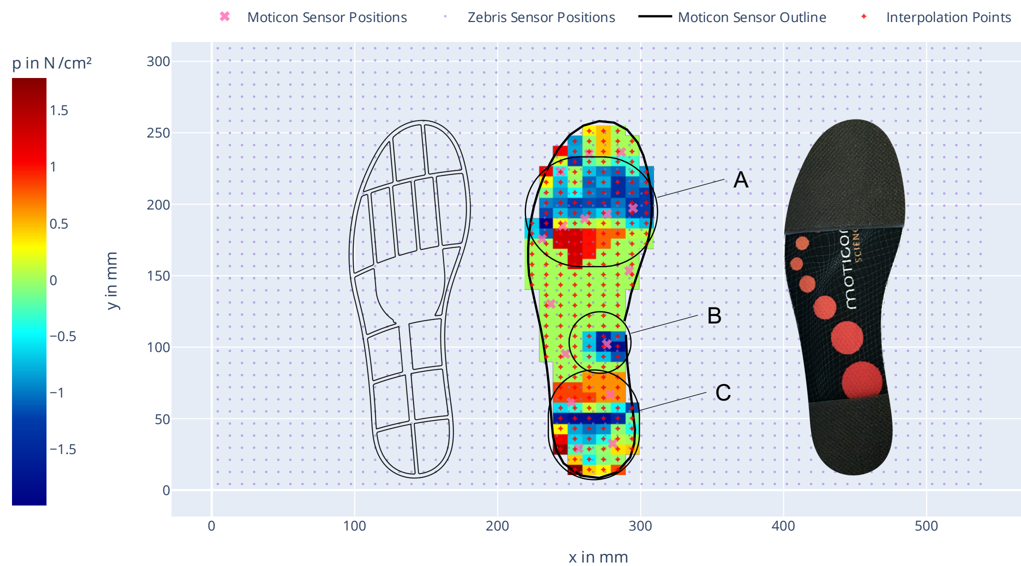

Figure 15: Foam, Size4, Left – Comparison between Moticon and Zebris on Interpolated Points

At the not loaded area (Y ≈ 75-160 mm) the average pressure difference is mostly close to zero. Significant differences occur at the edges of the foam pads (A and C), there the pressure difference changes the sign (+ 1.5 → -1.5 N/cm²). This indicates that the large sensors sizes of the Moticon system are not able to resolve the pressure gradient. The area labeled with B section around shows a deviation that coincides with the location of the insole battery compartment.

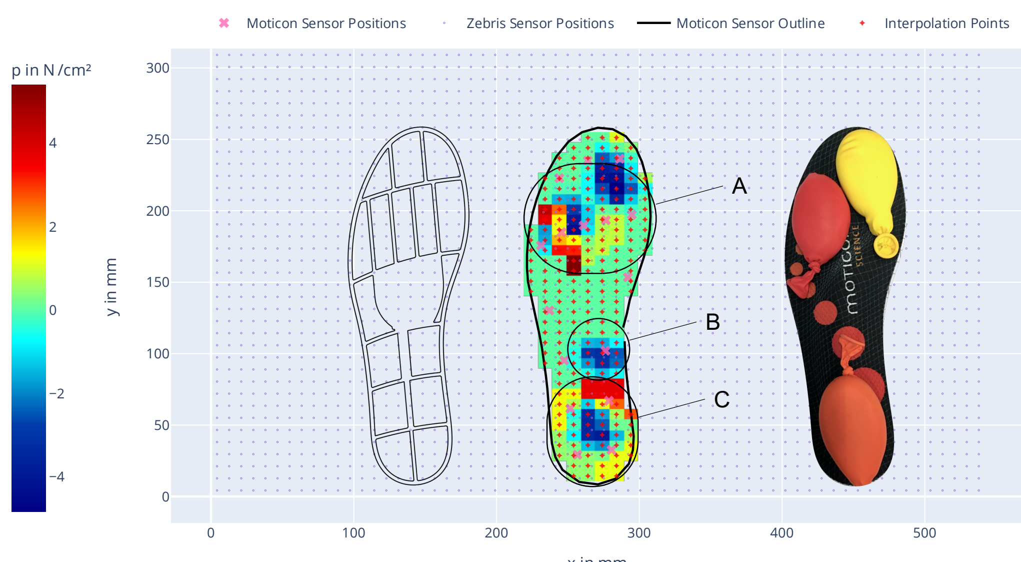

Figure 16: Sandbag, Size4, Left – Comparison between Moticon and Zebris on Interpolated Points

The pressure difference resulting from using sandbags is shown in Figure 16. While the area that is not loaded (Y ≈ 75-160 mm) shows good agreement, the loaded areas (A and C: ≈ -4 N/cm^2) show significant deviations, that are higher compared to the foam pad (see Figure 15). The maximal pressure at sandbags positioned at the heel and the medial toe are undervalued by Moticon. At the battery compartment (B) a noticeable difference is detected.

There is a remarkable variation in the pressure difference on the path from the center of the heel towards the battery compartment. Also, there are some distinct fluctuations in lateral forefoot area. These match the boundaries of the sensors.

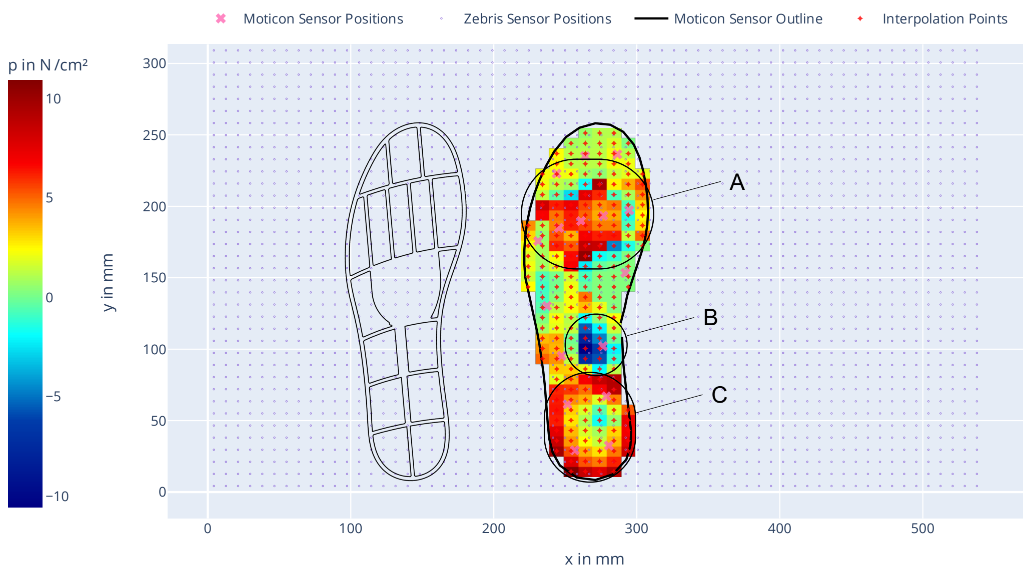

Figure 17: Human, Size4, Left – Comparison between Moticon and Zebris on Interpolated Points

While both sensor systems show good agreement for the pressure at the center of the heel (C at the center: ≈ 0 N/cm^2), the difference in the area around the center is significantly higher (C: +10 N/cm^2). A clear difference is also found at the forefoot (A: +5…10 N/cm^2) as well as at the area of battery compartment (B: -10 N/cm^2).

There is a clear trend, that shows that the absolute difference increases with the pressure level applied (Foam < Sandbag < Human). This clustering can be seen in Figure 18 which scatters by the minimal and maximal differences by load type and soles size. The three human size4 data points that are separated above the main cluster are linked to the right sole indicating a substantial difference between the left and right sole.

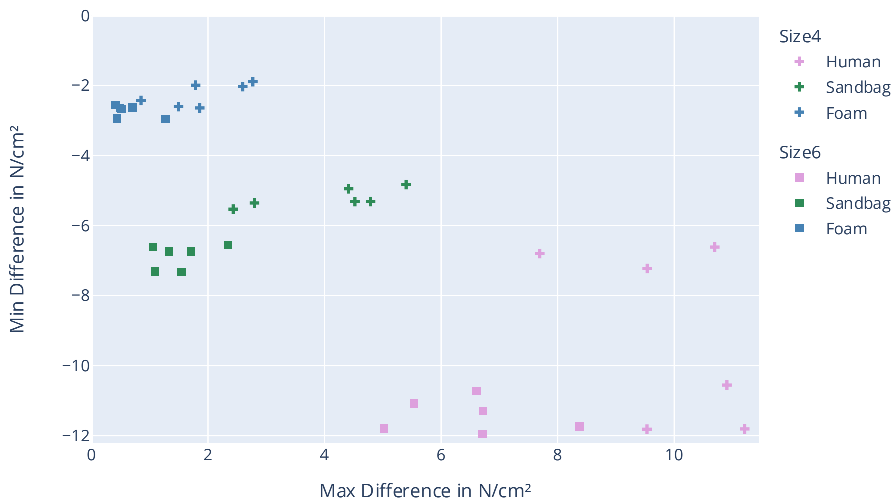

Figure 18: Max, Min Difference per Measurement per Sensor System and Load Type

In Figure 19 the relative error to the total weight that was applied to the sensor is shown. A difference between both systems is apparent. The mean errors and the range are substantially larger by the Moticon system (especially for Size4). The Zebris system seems to achieve slightly better results with higher loads, while the Moticon systems results are inclusive due to differences between the tested sole sizes. While Size4 produced better, yet not satisfactory results for the lower loads, Size6 gave good results regarding the mean error -4 % matching the Zebris system. But the range is significantly broader: 5 to -13 % compared to -3 to -4 % for the Zebris system.

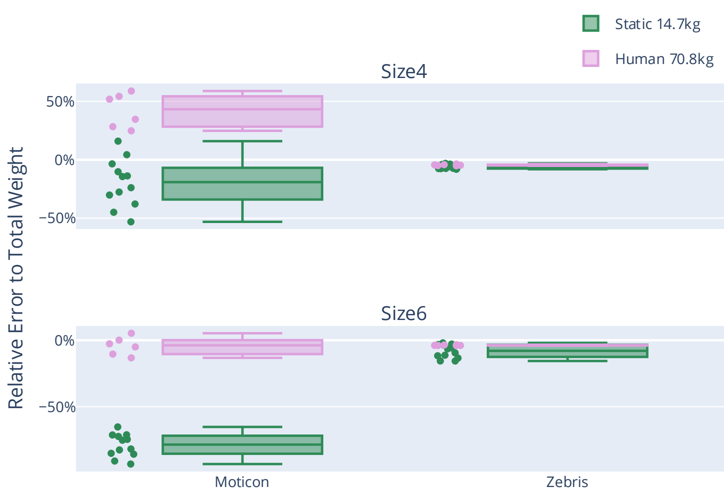

Figure 19: Relative Error to Total Weight per Sensor System and Weight Level

5.2.2 Distribution over Time

To compare the distribution over time the nearest Zebris sensor neighbor to a Moticon sensor center is selected to compare the values. The range and interquartile range are of interest, while the absolute mean values are less meaningful due to the averaging effect of different sensor sizes. But it is assumed that a match of relative positions of mean values indicates better agreement, e.g., matching the relative positions implies that the mean value at a sensor position y should be greater/smaller than at the surrounding sensor positions x, and z for both systems.

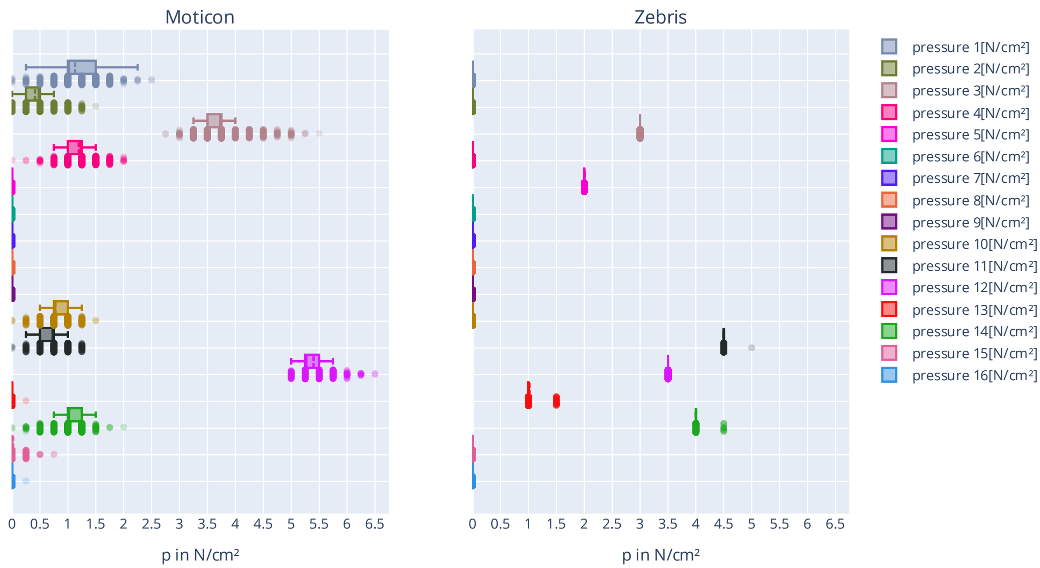

Figure 20: Sandbag, Left, Size4 – Distribution over Time

In Figure 20 a clear difference can be seen between the distribution over time for the two different sensor systems under a pure static load. While the data provided by Moticon shows significant spread over multiple divisions of the sensors, the Zebris data does not. However, it must be noted that the Zebris System has a larger division of .5 N/cm^2, and most Moticon data show an interquartile range of .5 N/cm^2. Yet the range of Moticon sensor readings are very wide by comparison. The behavior for the foam pads is similar to the sandbag.

Figure 21 shows the distribution over time in the case a human loads the sensor systems. In that case data from both systems show a wider spread compared to the pure static loaded case, which is expected since the human must balance. However, the width of the distributions is greater in the Moticon data. Comparing the distribution between sandbag and human, the respective mean values are closer relative to each other implying a better agreement. (Note the changed scaling of the x axis.)

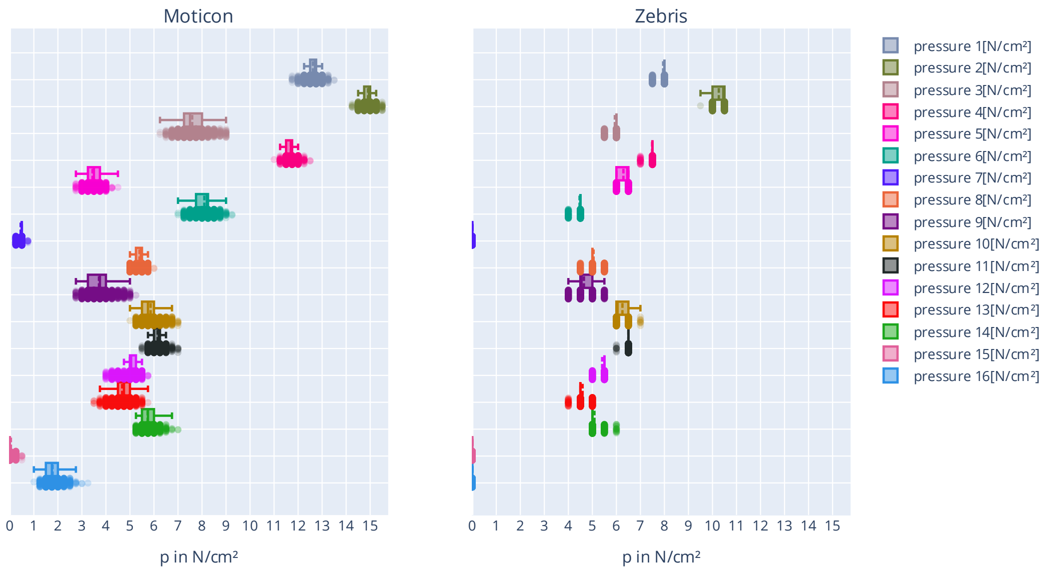

Figure 21: Human, Sole4, left: Distribution over Time

5.3 Discussion

With regards to the spatial comparison of insole and plate pressure distribution, the selected method (nearest neighbor interpolation) introduces a methodical error at the center of the insole since there is no sensor located there. However, apart from the foam pads the described differences where not close to this area.

The spatial resolution of the Moticon system with larger sensor sizes compared to Zebris system is less capable to detect local changes in pressure field. This averaging effect [21] due to large sensor is one of the main influences to the differences in the pressure distribution. The spatial comparison showed that at locations with high pressure gradients, the difference within a Moticon sensor can change over the area of the sensor significantly. Furthermore, the Moticon system seems not to be self-aware of its battery compartment, that can be felt by the user and produces consistent negative difference between both systems for all load types, even though the battery compartment is not loaded by the sandbags and foam pads directly.

Comparing the nearest Zebris sensor reading to the Moticon data over time shows that the Zebris system introduces less noise. This was very apparent in the static tests. While the mean values are not directly compared, their relative position to the other values is compared between the static load cases and the human load case. In the latter the difference is less apparent. It is concluded that the signal noise properties of the Zebris system is much more favorable for pure static tests.

Regarding the methods used, the accuracy of the comparison might be improved by accounting for the actual sensor form of the Moticon system. In the spatial comparison the values could be assigned to all the interpolations points within a sensor, leaving interpolation outside of actual sensors as NaN[12]. And for the comparison over time the Zebris data within the individual Motion sensors could be spatially averaged per time step. But since the information needed for that was not readily available and the reduction in the error by using the actual sensor form seems to only make slight improvements to the comparison methodology, it was deemed not rewarding enough.

Due to the measurement setup the Moticon system could not be software calibrated and had to be manually zeroed, which might result in poorer performance. However, from the experience in the other study and due to the static nature of the exercise the strict automatic zeroing mode seems to be impractical. From the results it is concluded that the Moticon system in general is not as suitable to static loading as the Zebris system.

6 Conclusion

A new research software tool was presented. The software requirements, the hard- and software architecture and some implementation details were outlined. The concept of *muscular controlled standing* was introduced by discussing the foot and giving a reasoning about the biomechanical importance of the muscle activation to support the body. An exercise to train the activation of the muscles was proposed. The implementation of the *Force Triangle* criterion to evaluate the exercise was outlined as well.

Finally, two studies were conducted. The first aimed to select parameters for the proposed *Force Triangle* criterion. The study did not provide data that is deemed suitable to proceed the process of weight selection outlined in chapter 3.2.1. Furthermore, the results questioned the suitability of the Moticon sensor system for the type of application, i.e., nearly static pressure distribution. Hence, a comparative study was conducted to compare the Moticon system to a pressure distribution plate manufactured by Zebris. The second study substantiated the concerns about the suitability of the Moticon insoles.

An overview of the characteristics of the compared sensor system based on the experiences gained in the development and the conducted studies is given in Table 2.

[12] Not a Number, since there is no actual value there.

Table 2: Characteristics of the Sensor Systems

	Moticon		**Zebris**
–	Poorer spatial resolution	+	Good spatial resolution
–	Noisy sensor signal	+	Sensor signal not noisy
–	Poor repetitive accuracy	+	Good repetitive accuracy
+	Fixed relative position of sensors and foot	+	All types of foot
–	Insole outline do not match different morphological types of foot/shoe	–	A priori unknown relative position of sensors and feet.
+	Easily transportable	–	Limited mobility
+	Low space requirement13	–	High space requirement[14]
–	Automatic zeroing not suitable for static exercises	–	Higher price

This Table does not intend to include all pro and cons, as there are other considerable characteristics as frequency, possible places of usage or synchronization possibilities. The first three points reflect upon the results from chapters 4 and 5. The Other points are important to note due the type of application in which the sensor system should be used in the future. One of these relates to the fact, that the insoles are worn inside shoes, which bonds the sensors to the foot hence making the relative position of the sensors and the foot known a priori. This is not the case for plate-based systems since the user is free to stand on the plate at any position. On the other hand, the form of sensor insoles cannot match all different types of foot and might therefore produce errors. These different types are the result of the skeletal structure and the surrounding connective tissue of the foot forming certain morphological foot types that might additionally exhibit individual deformities.

While there was an expectation that sensor insoles will not perform as good as sensors plates [5], the difference especially regarding the repetitive accuracy and the signal noise in a static application led to the conclusion that the Moticon system is not suitable for the application. The Zebris system on the other hand has good characteristics regarding these two properties but it will not allow the usage of the system at a patient's home, due to the transportability, space, and price concerns.

[13] Storable in a compact suitcase
[14] Approx. 1.6m x 0.6m

Going forward, the GINSODA software tool will be adapted to the Zebris system. This will pose specific challenges that are inherent to a platform-based system: How to detect the position and rotation of the foot on the plate based on the pressure distribution or any additional information? The decision to change the mayor sensor input has implications for the implementation details, the software architecture however can remain the same. This will allow the development and testing of evaluation criteria in later trails with the Zebris system. Ideally, technological improvements will allow the usage of insole sensors later, since they have properties that might allow unsupervised usage at home in the future. And by this might support people sustain and improve the health of their motor-controlled system without the supervision of a therapist.

Acknowledgements

This publication was produced as part of the BewARe project with the name: Sensor-supported movement training for senior citizens in an intelligent Augmented Reality System. The BewARe project is a three-year (08/2018 - 08/2021) R&D project founded by the German Federal Ministry of Education and Research (BMBF). Project website: https://www.beware-projekt.de/en/index.html.

Literatur

[1] R. Koch-Institut, “Bericht Gesundheit in Deutschland 2015,” p. 516, 2015.

[2] IGES Institut GmbH, Terese Dehl, Susanne Hildebrandt, Jelena Sörensen, and Kai-Michael Kleinlercher, “Länderübergreifender Gesundheitsbericht Berlin-Brandenburg 2019.” Clustermanagement Gesundheitswirtschaft Berlin-Brandenburg – HealthCapital Berlin Partner für Wirtschaft und Technologie GmbH, Dec. 2019. [Online]. Available: www.healthcapital.de/gesundheitsbericht2019

[3] S. Chen *et al.*, “Global, regional and national burden of low back pain 1990–2019: A systematic analysis of the Global Burden of Disease study 2019,” *J. Orthop. Transl.*, vol. 32, pp. 49–58, Jan. 2022, doi: 10.1016/j.jot.2021.07.005.

[4] M. A. Adams, *Rückenschmerz und Lendenwirbelsäule: interdisziplinäres Praxisbuch entsprechend der Nationalen VersorgungsLeitlinie Kreuzschmerz: mit 360 Abbildungen*, 2., Überarbeitete Auflage. München: Elsevier, Urban & Fischer, 2012.

[5] T. Stöggl and A. Martiner, “Validation of Moticon’s OpenGo sensor insoles during gait, jumps, balance and cross-country skiing specific imitation movements,” *J. Sports Sci.*, vol. 35, no. 2, pp. 196–206, Jan. 2017, doi: 10.1080/02640414.2016.1161205.

[6] R. Eguchi, A. Yorozu, T. Fukumoto, and M. Takahashi, “Ground reaction force estimation using insole plantar pressure measurement system from single-leg standing,” in *2016 IEEE International Conference on Multisensor Fusion and Integration for Intelligent*

Systems (MFI), Baden-Baden, Germany, Sep. 2016, pp. 109–113. doi: 10.1109/MFI.2016.7849475.

[7] R. Beaner, “COMPARISON OF PRESSURE SENSOR INSOLES TO THE GOLD STANDARD,” p. 16.

[8] Christopher Kümmel *et al.*, “BewARe - Sensor-based Augmented Reality system for individualized endurance training for elderly people,” presented at the IEEEVR, Osaka, 2019. [Online]. Available: http://hildebrand.beuth-hochschule.de/beware/ieeevr_aveh_final.pdf

[9] K. Hildebrand, F. Steinicke, S. Rings, C. Kümmel, P. Wesberg, and J. Villwock, “VITALabs - A Multi-Stage Platform for the Evaluation of Virtual Therapies,” p. 3, 2019.

[10] T. Schmelter, S. Rings, C. Prasuhn, J. Villwock, F. Steinicke, and K. Hildebrand, “VITALab.Mobile - A Mobile Living Lab,” in *Proceedings of Mensch und Computer 2019*, Hamburg Germany, Sep. 2019, pp. 917–920. doi: 10.1145/3340764.3345381.

[11] I. Sommerville, *Software engineering*, Tenth edition, Global edition. Boston Columbus Indianapolis New York San Francisco Hoboken Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montreal Toronto Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo: Pearson, 2016.

[12] I. A. Kapandji, *The physiology of the joints - the lower limb*, 6th ed., English ed., vol. 2, 3 vols. Edinburgh ; New York: Churchill Livingstone, 2011.

[13] W. Platzer, *Bewegungsapparat*, 7., Vollst. überarb. Aufl., vol. 1, 3 vols. Stuttgart: Thieme, 1999.

[14] J. Hochschild, *Strukturen und Funktionen begreifen. 2: LWS, Becken und Hüftgelenk, untere Extremität*, 2. Aufl. Stuttgart: Thieme, 2008.

[15] J. Dudel and R. Blickhan, Eds., *Neurowissenschaft: vom Molekül zur Kognition; mit 32 Tabellen*, 2., Überarb. und aktualis. Aufl. Berlin Heidelberg: Springer, 2001.

[16] G. E. Loeb, “Control implications of musculoskeletal mechanics,” in *Proceedings of 17th International Conference of the Engineering in Medicine and Biology Society*, Montreal, Que., Canada, 1995, vol. 2, pp. 1393–1394. doi: 10.1109/IEMBS.1995.579743.

[17] G. E. Loeb, I. E. Brown, and E. J. Cheng, “A hierarchical foundation for models of sensorimotor control,” *Exp. Brain Res.*, vol. 126, no. 1, pp. 1–18, Apr. 1999, doi: 10.1007/s002210050712.

[18] H. Frisch, *Programmierte Untersuchung des Bewegungsapparates: Chirodiagnostik*. 1998. Accessed: Jun. 08, 2022. [Online]. Available: http://link.springer.com/openurl?genre=book&isbn=978-3-662-09494-5

[19] Moticon ReGo AG, “Moticon SCIENCE Sensor Insole Product Specification.” Moticon ReGo AG, Jan. 2020.

[20] Moticon ReGo AG, “Moticon Application Note 003 Sensor Insole Geometry.” Moticon ReGo AG, Nov. 2020.

[21] T. C. Pataky, “Spatial resolution in plantar pressure measurement revisited,” *J. Biomech.*, vol. 45, no. 12, pp. 2116–2124, Aug. 2012, doi: 10.1016/j.jbiomech.2012.05.038.