3D Scanning Smart Glove for Shape and Softness of a Patient's Body in Orthopedic Applications

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Abstract

The sendance-glove measuring system metaphorically turns the hands of healthcare professionals into a 3D scanner for the shape and softness of a patient's body. It is a scanning glove with combined pressure and position sensors embedded in a silicone matrix, which makes it possible to transform tactile information into digital data directly usable for designing mobility aids and orthopedic devices, such as ankle-foot orthoses and custom orthopedic shoes. To the best of our knowledge, capturing the implicit knowledge embedded in an expert's fingertips via a scanning glove is a completely new approach to digitize healthcare. The sendance-glove system allows designing orthopedic devices without artisan processes like plaster casting or tape measuring. The position sensors, which work with a measurement principle based on electromagnetic induction, identify the fingertips' positions with <1 mm precision. The pressure sensors developed by sendance GmbH are small (6mm diameter, 0.3 mm thickness), built from a flex-PCB and a thin film of piezoresistive material. Integrated in the glove, they are calibrated over a pressure range of 10 - 250 kPa to achieve high precision and repeatability. The core functionality of the glove scanning system is realized when data from the pressure and position sensors are correlated. With data pairs of both pressure and position captured at the same time, functionalities such as shape surface detection, distance measurement and tissue hardness estimation can be achieved.

Keywords: 3d body scanning, smart glove, orthopedic engineering, position sensors, pressure sensors, sensor fusion, ankle-foot orthoses

1. Introduction

New technologies can greatly improve the efficiency and effectiveness of healthcare delivery as they get adopted to health professionals needs and workflows. Foot problems are a common health issue amongst adults and foot orthoses are crucial for treating these problems. However, current methods for creating orthoses are often labor-intensive, time-consuming, and environmentally harmful. Smart sendance-glove can help address these challenges.

It is estimated that up to 87% of the population experience foot problems at some point in their lives based on the Health In Aging Foundation (www.healthinaging.org), necessitating orthopedic devices. Despite the relatively common use of ankle-foot orthoses, approximately 20% of corrective measures fail to alleviate pain [1,2]. This high failure rate is not due to a lack of skill but rather a lack of quantitative data [3] to be used for defining the metrics for sufficient corrective measures.

Foot and ankle treatment in orthopedic practice is unique because a significant number of patients are managed non-surgically, often with the use of orthoses. An orthosis is an externally applied device designed to modify the structural and functional aspects of the neuromuscular and skeletal systems. Orthoses are used for one or more of the following purposes: pain relief, managing deformities, restricting or promoting joint movement, correcting neuromuscular imbalances, compensating for abnormalities in body segment shape or volume, and protecting tissues during healing [2]. The design of orthopedic devices relies heavily on experiential knowledge tied to practical evidence. Orthopedic engineers understand what works, but there are multiple vague rules of thumb, meaning evidence-based knowledge is lacking. We have developed a technology that transforms the extensive knowledge that pedorthists have acquired over many years into explicit sensor data and metrics. This not only ensures the creation of high-quality orthoses but also serves as a valuable resource for educational purposes.

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Depending on the complexity of the orthoses - whether insoles, ankle orthoses, or customized shoes - an orthopedic engineer typically requires 3-4 appointments for measurements and design verification. Based on our consultations with orthopedic engineers, the average session duration ranges from 30 to 60 minutes. This time-consuming process involves multiple manual measurements, which can be made significantly more efficient by increasing the measurement accuracy and transferring the data automatically to a Computer-Aided Design (CAD) application software for the creation of shoe lasts, insoles, or orthoses. To design orthoses, it is essential to obtain a model of the limb in a corrected position, either through plaster casting or digital scanning. Additionally, information about joint axes and bony prominences is transferred to a computer manually, to select the appropriate shoe last and apply various cushioning materials. Several challenges arise when designing orthotic devices, whether using digital scanners or casting materials [4]. For example, digital scanning struggles to remove the hand that corrects the limb's position from the resulting 3D model without manual intervention. On the other hand, working with plaster casts is time-consuming, requires a significant amount of materials, and is therefore environmentally unfriendly. In addition to measurements, communication between the last manufacturer and the orthopedic engineer is essential to ensure the accuracy of the last type and the interpretation of measurements.

To address these limitations, we introduce the sendance-glove, a smart glove equipped with pressure and position sensors that (figuratively) transforms the hands of healthcare professionals into a 3D scanner for shape and softness. This technology aims to digitize the knowledge and practice of orthopedic experts [5], enabling the direct capture and quantification of tactile information during patient assessments.

With this new smart glove tool the plaster cast of the foot can be replaced by a digital representation of the geometry of the foot. To further improve the efficiency of the workflow, it is also possible to only capture specific reference points that are sufficient to manufacture customized orthotic devices.

The goals of the presented solution are:

1. Decreasing the labor effort for orthopedic engineers in terms of time shortening and less cumbersome work with material casting and manual procedures for orthoses design.
2. Increasing the quality of data by providing the exact positions and tissue information of the labeled points.
3. Providing a new dimension of objective data, aiming to derive clear metrics and standards for the digital treatment of patients with musculoskeletal diseases.

We aim to bridge the gap between experiential knowledge and quantitative data to streamline the design process and improve the quality and thereby effectiveness and reliability of orthopedic devices.

This paper details the system itself including essential components, manufacturing and algorithmic considerations, as well as a prototypic demo software. Additionally, we present results from exemplary applications and discuss integration options, further application areas, and current limitations.

2. Material and methods

This section outlines the key hardware components necessary for constructing the smart glove, the most important steps of the manufacturing process, and introduces exemplary software capabilities for implementing functions such as distance measurement and hardness assessment.

2.1. Pressure and position sensor systems

The pressure sensors and their readout electronics are developed by sendance GmbH [6].They work on the basis of the piezoresistive principle and consist of a thin sheet of piezoresistive material attached to the top of two electrodes. The pressure sensors used in the glove have a thickness of less than 0.3 mm and a length of 7 mm. Each of the sensors is individually calibrated up to a pressure of 250 kPa to account for manufacturing variability between individual sensors, but they are robust enough to withstand a pressure normal to their surface of more than 500 kPa and shear forces that appear in a glove during normal usage without damage.

To record the position of the fingertips, the commercially available position sensing system Aurora® by the company Northern Digital Inc. (NDI) is used. The main components of the system are the field generator, the Sensor Control Unit (SCU), the Sensor Interface Unit (SIU) and the position sensors (Fig. 1).

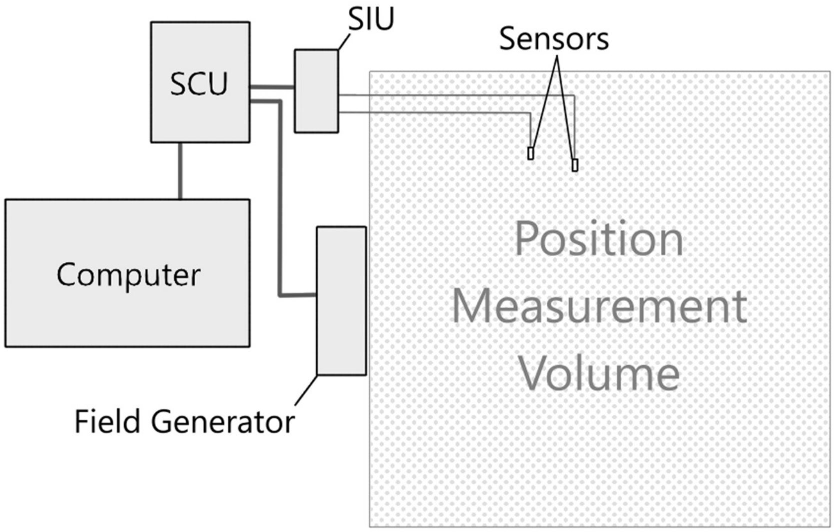

Fig. 1. Schematic of the main components of the Aurora® position sensing system and their connections.

For all experiments in this paper, the 5D.P05.09-1 position sensors from NDI are integrated in the fingertips, which have a thickness of 0.45 mm, length of 8.2 mm and a position root mean square (RMS) error of 0.56 mm when used together with the Field Generator Planar 20-20. The latter has a cubic position measurement volume with a side length of 0.5 m in front of the field generator. Its field generator emits a pulsed electromagnetic field, which induces a signal in the position sensors that can then be used to calculate the position and orientation of the sensors relative to the field generator.

2.2. Manufacturing the sendance-glove

It is necessary that the sensor pair is as close together as possible to ensure that the position-pressure data pair can be attributed to a point in space with minimal error, so the center of the pressure sensor is put directly on top of the position sensor. This configuration also protects the sensitive position sensor from being bent too strongly. To improve stretchability, the wires to the sensors are configured in a meander shape (Fig. 2).

The sensors and wires are encapsulated in the silicone Ecoflex 00-50 from both sides, to a total thickness of 2.6 mm at the fingertips and 1.6 mm at the wiring on the back of the hands. The silicone leads to a higher robustness of the soldering joints, better pressure distribution on top of the sensors, and also provides the restoring force to push the meandered wires back in place after stretching.

An adhesive paper base layer and a 3D printed border are used at the beginning of the fabrication process to help with portability and silicone encapsulation. These components are removed at later steps during the process. The sensor array of the final glove only consists of the sensors, their wiring and the silicone they are encapsulated in.

To ensure that solder joints and sensitive parts of the electronics cannot be easily damaged or touched by conductive objects, they are packaged in a 3D printed shell. The shell can be placed at the wrist and contains the pressure sensor readout printed circuit board (PCB), the connection of the position sensor cables to the tool cables going to the SCU, and openings for the charging and data readout cables. The sensor data from both the sendance pressure sensor system and the NDI position sensor system can be accessed via serial interface.

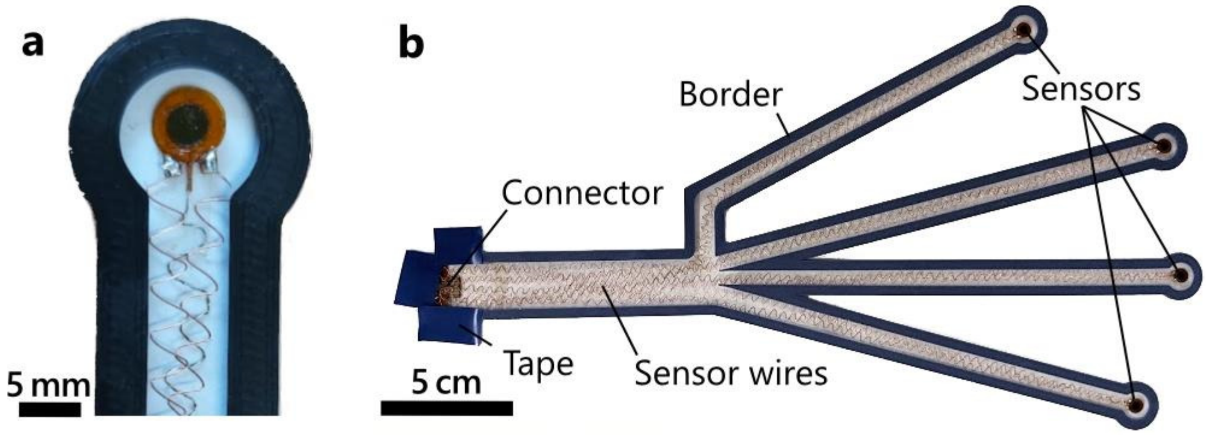

Fig. 2. Pressure and position sensor connected to meandered wires inside the finger border at the start of the glove manufacturing process

2.3. Recording surface and distances

The data of the two sensor systems is transmitted simultaneously over the serial interfaces and displayed live in a demonstrator program written in the language Python (Fig. 3). A data rate of 5 Hz is reached in the demonstrator due to its prototypic nature, but the position and pressure sensor systems themselves support up to 40 Hz and more than 80 Hz, respectively. Therefore, a data transfer rate of 40 Hz to a CAD program is achievable.

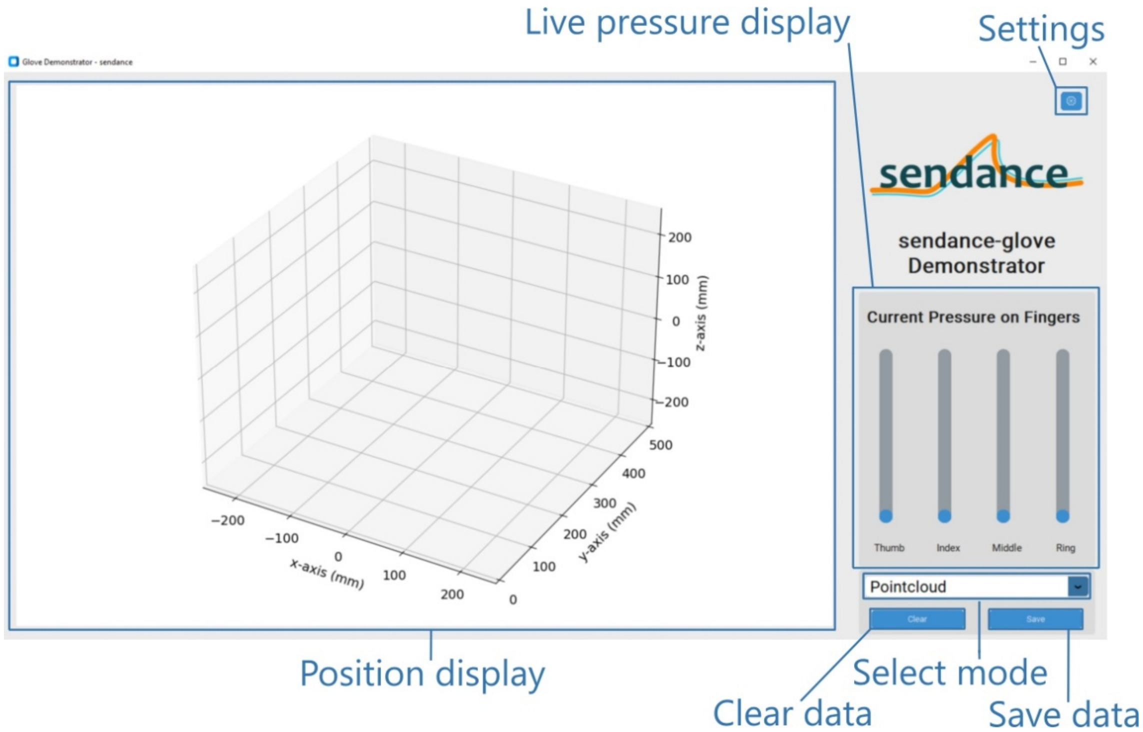

Fig. 3. User interface of the sendance-glove demonstrator program

To record surface positions, the pressure value p_i of each finger i is compared to a pressure threshold p_{th}. If the reached pressure is above the threshold, it is possible to assume that the finger is currently pushed against the surface on the object, and that the finger position obtained by the corresponding position sensor is a surface point. It is not sensible to put this threshold at p_{th} = 0 kPa because flexing the fingers causes tension in the fabric and silicone. This tension exerts a small pressure on the sensors and would lead to incorrect recorded surface points if the threshold is too low. Experiments showed a threshold value of around p_{th} = 20 kPa is sufficient.

To record distances, a separate mode in the demonstrator program calculates and displays the Euclidean distance d_{jk} between the latest two points. Instead of saving all points where the pressure threshold is exceeded into a list, a new point is only added if its Euclidean distance to the previous two saved points exceeds 2 mm. This method ensures that only the distance between the intended two points on the surface are measured instead of the negligible distance between two consecutively recorded points at the same position sensor.

2.4. Hardness assessment

To assess the hardness of tissue, the user of the glove can slowly press into the tissue normal to its surface. Correlated pressure-position data pairs are collected from the finger, starting from the time where the pressure exceeds a set threshold, up until the point where the pressure on that finger decreases again, because the finger is lifted off the surface. The first position data point in the list is considered the surface point, and from each consecutive data point the euclidean distance to the surface point is calculated.

If the tissue layer has a roughly uniform hardness and is not too thin, it is possible to estimate this tissue hardness with a linear fit in the distance over pressure graph. Due to imperfect time synchronization between the sensor systems, the first data pair is not taken into consideration in the fit, but could be in a future version, to stabilize results. A higher slope corresponds to a softer tissue, since it is possible to press into tissue deeper if it is softer when applying a fixed amount of pressure.

If there are too few data pairs in the measurement or the total pressure range is too low, the hardness measurement is considered as invalid since there is not enough data. Preliminary experiments suggest that at least five data pairs should be collected and the total pressure range of the data pairs should exceed 25 kPa, but this may vary depending on setup and application.

3. Results

3.1. Shape

Due to the compression of the silicone, the intrinsic position sensor error and errors due to the size of the sensors, the surface position can be detected with an accuracy of about 1-2 mm. For an extensive 3D surface scan, it is necessary that the measured object does not move in reference to the field generator. Later versions could introduce reference sensors to remove this need.

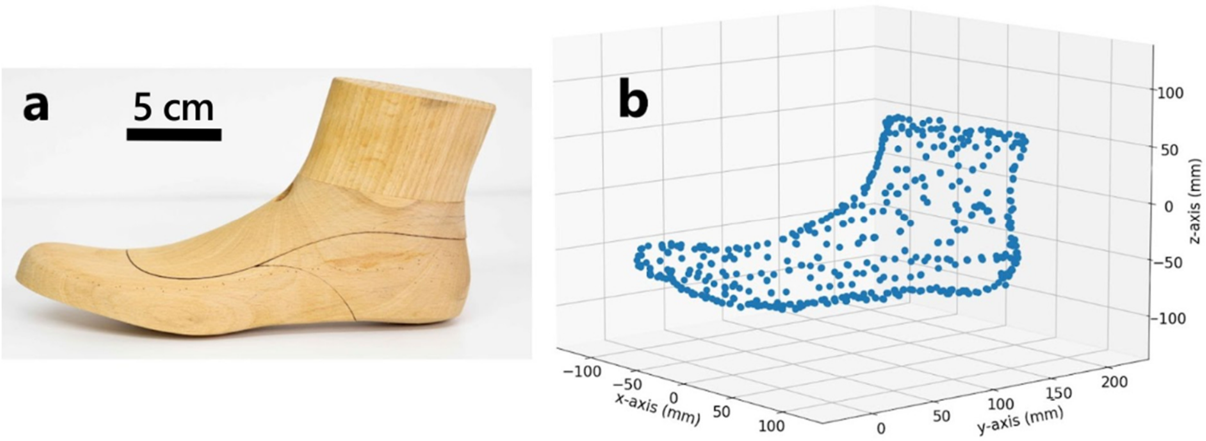

*Fig. 4. **a)** Wooden foot model, **b)** Resulting 3D surface point cloud obtained with the sendance-glove*

Figure 4 shows a wooden foot model and the 3D scan obtained with the sendance-glove. Such a scan takes about four minutes, but it is possible to drastically reduce that time if fewer surface points are required. Each point is recorded by briefly pressing down on each desired surface point, whereas multiple fingers can be used simultaneously.

3.2. Distance

When characterizing, e.g., a foot, most of the common orthopedic parameters (see, for example, [7]) can be measured by gripping both desired end points at the same time (Fig. 5). This immediate distance result has the advantage that no error can occur due to the patient moving between two touches. To measure distances which exceed the maximal distance between two "sensor fingers" of the operator, it is necessary to successively touch the two end points or use two gloves at the same time.

To demonstrate a proof-of-concept for using the sendance-glove to measure distances and estimate the accuracy that can be achieved with the glove, ten key anatomical foot parameters were measured with both the glove and a caliper. In this exemplary measurement, the relative errors of the glove compared to the precise caliper measurement are in the range of -2.5 % to 5.4 %, with an average absolute relative error of 2.6% (Tab. 1).

Tab. 1. Exemplary comparison of orthopedic parameters obtained with the sendance-glove with values obtained from a caliper measurement.

Parameter	Caliper measurement	Glove measurement	Relative error
Instep height	59.8 mm	58.6 mm	-2.0 %
Instep distance	95.2 mm	93.4 mm	-1.8 %
Heel width	64.9 mm	68.4 mm	+5.4 %
Heel circumference	-	-	-
Ball height	36.2 mm	37.8 mm	+4.4 %
Ball width	85.7 mm	84.1 mm	-1.8 %
Ball circumference	-	-	-
Arch length	144.1 mm	150.0 mm	+4.1 %
Lateral Metatarsal Length	136.1 mm	135.7 mm	-0.3 %
Medial Metatarsal Length	154.0 mm	157.9 mm	+2.5 %
Foot width	81.4 mm	79.7 mm	-2.1 %
Foot length	222.7 mm	218.3 mm	-2.0 %

Parameters like heel circumference and ball circumference can not be measured using only one sendance-glove and a single touch. However, an approximation of circumferences can be obtained in a workflow that requires the operator to touch at least two evenly spaced points around the circumference. The circumference can then be estimated by calculating the total length of elliptical arcs connecting the points.

Some parameters like the arch length require a projection of a distance along a plane. While these parameters can be measured with the sendance-glove just as well as with a caliper or measurement tape, measurement precision could be significantly improved by using one or two reference position sensors in a fixed orientation to the foot, or simply touching reference points at the start of the workflow (assuming the foot remains stationary).

*Fig. 5. Measuring the **a)** heel width, **b)** ball height, **c)** ball width with the glove.*

3.3. Hardness

In this example, we successfully differentiated four reference cubes with a shore hardness of 00-10, 00-20, 00-30 and 00-50 respectively, and a wooden table, which is essentially incompressible with the glove and human strength, at least to a significant degree (Fig. 6). The cubes are made from silicone and have a side length of 4 mm.

It needs to be noted that the glove only approximates the shore hardness, as a definitive measurement requires a standardized indenting foot and measurement procedure [8]. However, even an approximate relative hardness distribution offers valuable information for orthotics design. It can eliminate the need for manual marking of bones, wounds, and unusual tissue abnormalities. Identical cubes of different shore hardness can serve as good reference values for the functionality of the glove. The shore hardness range 00-10 to 00-50 was chosen due to the fact that it corresponds well to the usual hardness range of foot tissue [9].

The calculated slope of one object with constant hardness sometimes differs between two fingers of a glove, which is most likely due to the pressure distribution effects of the silicone and the textile layer, or pressure sensor drift after calibration. To get the same results for all pressure-position sensor pairs, the calibration procedure of the sensor integrated into the glove needs to be investigated further, as well as the current, rather simplistic, hardness estimation algorithm further developed and optimized.

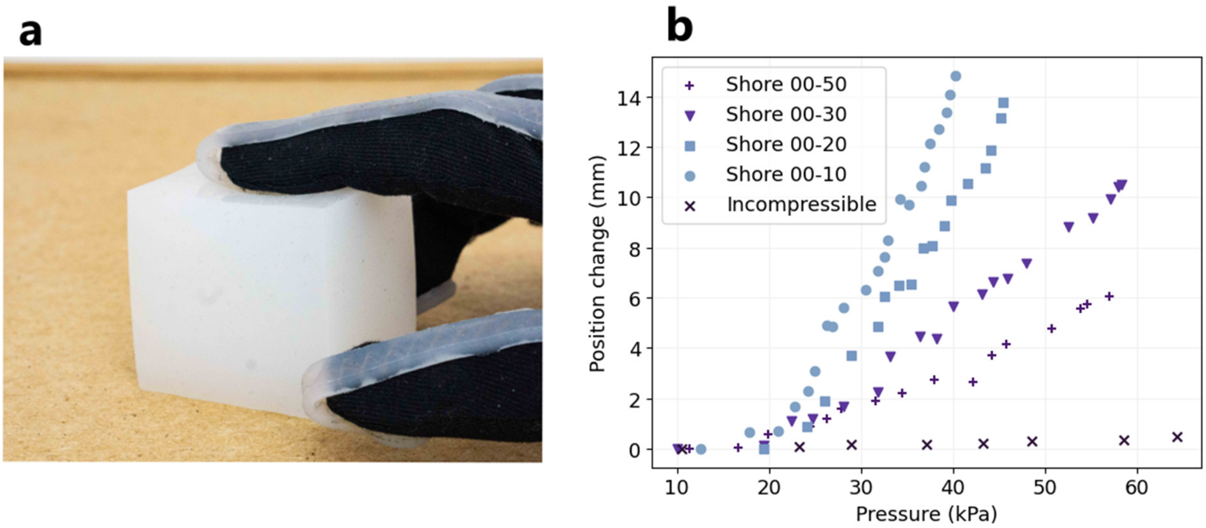

*Fig. 6. **a)** Silicone reference cube, **b)** Correlation between position change and pressure at different shore hardness*

4. Discussion

4.1 Orthopedic applications of the sendance-glove

A main application of the introduced smart glove is to help orthopedic engineers accelerate the creation of orthopedic devices while minimizing environmental impact. It can enhance the quality of these devices by digitizing manual processes.

The conventional process of creating a shoe last for custom orthotic devices involves:

1. Multiple manual measurements on the patient's limbs and identifying areas that require specific cushioning materials. This process is time-consuming, as measurements require manual data entry into orthopedic forms.
2. Selecting the appropriate last model based on the patient's limb measurements. Decisions about the last model and material hardness are often subjective and can introduce errors since they are made through back-and-forth communication with the shoe last manufacturer. Using a dataset measured with the smart glove, this required communication is reduced.
3. Final adjustments once the orthopedic engineer receives the last, meaning any inaccuracies in the last can lead to needing additional labor and time for corrections. The data quality of the glove can likely reduce the need for extensive corrections.

The sendance-glove could be easily integrated into an orthopedic engineer's workflow by installing a sendance plug-in software - a driver-like app with an interprocess communication application programming interface (IPC API) - that transfers sensor and evaluation data from the glove directly into a CAD application (Fig. 7). The data transferred into the CAD system are: the distances between points of choice, tissue hardness at the points of choice, and possible reference point coordinates.

With this data obtained from the smart glove, in the example of last model design for an ankle orthosis, the conventional workflow is significantly shortened via possibilities like:

1. Automatic insertion of the measurements between anatomical labels (Tab. 1) into orthopedic forms.
2. Automatically scaling a standard last model according to the limb measurements. For example, a standard shoe last model can be either selected by the orthopedic engineer from a library based on the foot type (e.g., flat feet, high arches), or automatically selected based on the ratio between anatomical markers [7], though this option requires more advanced algorithms.
3. Displaying and recording tissue hardness data both of pre-defined anatomical landmarks and at additional points specified by the orthopedic engineer (e.g., wounds).

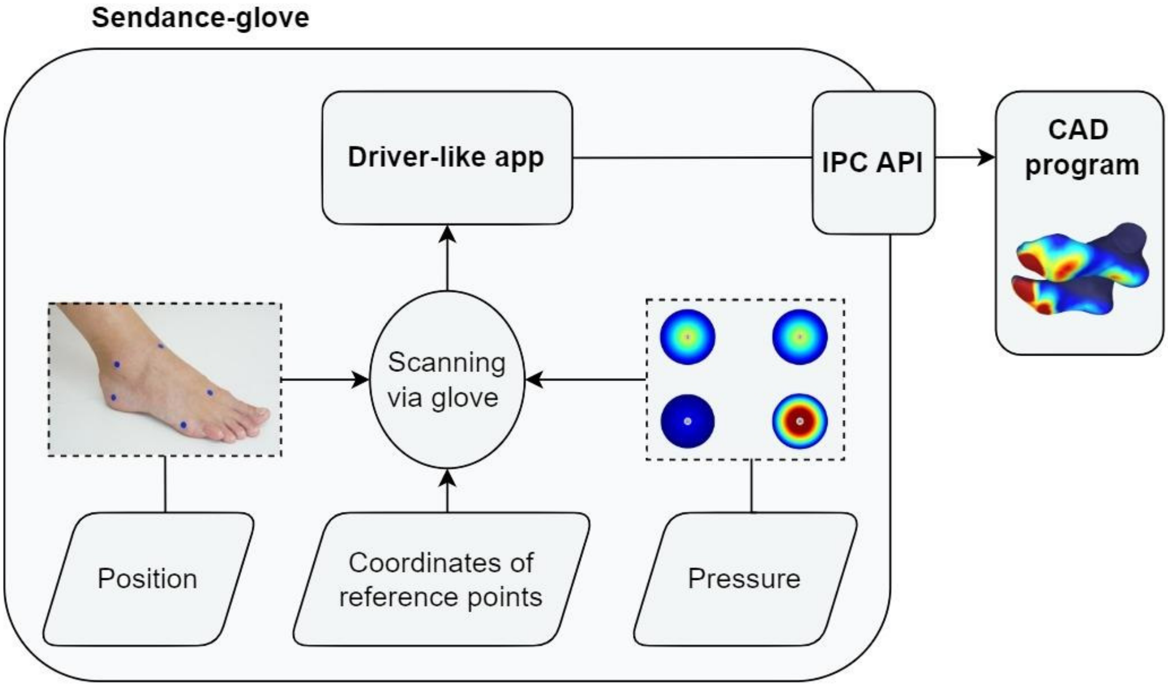

Fig. 7. Data flow in the sendance-glove hardware and software

Apart from the illustrated ankle orthosis design, several other orthopedic applications are promising with the technology of the sendance-glove, like prosthetic socket creation with integrated spatial and tissue hardness data, and customized insole design accounting for variations in tendon, muscle and bone hardness.

In addition to streamlining the process to save time, using the sendance-glove also increases patient comfort and decreases environmental impact because no resource-intensive processes such as plaster casting are required.

4.2. Potential other applications of the sendance-glove

Enhancing human hands with the ability to sense material hardness and finger positions, potentially in addition to temperature, humidity, and other surface properties, opens up multiple opportunities for innovation and practical applications. To mention a few:

1. Robotics, by enabling robots to "learn" optimal forces and contact points for handling various objects
2. Tactile/palpation diagnostics by providing objective, quantifiable measurements of tissue properties during clinical examinations
3. Ergonomic risk factors assessment linked to musculoskeletal disorders by quantifying pressure distribution and hand posture and analyzing this data

4.3. Limitations and further improvements

In the current prototype, the calibration of the pressure sensor system integrated into the glove and the time synchronization between the sensor systems has not been investigated in detail yet. While the current data quality is good enough for shape and distance measurements as well as rough differentiation of tissue hardness, further improving the data quality could enable more nuanced tissue detection, like detecting small tendons or tumors.

For the application case of an orthopedic engineer, further consideration needs to be put into hygiene, rigorous robustness testing and enhanced algorithms for tissue differentiation. Hygiene is a concern because the sendance-glove will be used by multiple patients and orthopedic engineers, necessitating hygiene protocols and materials that can be easily cleaned or disinfected. Regarding robustness, the glove and its sensor systems must be built in a way to withstand repeated daily use, especially sensitive areas like the soldering joints. Tissue hardness measurements should be adapted for specific tissue types, requiring the development of sophisticated algorithms and/or application of machine learning to accurately interpret the sensor data.

5. Conclusion

The sendance-glove has the potential to significantly improve orthopedic practices by enabling the direct digitization of tactile assessments and streamlining device design processes. The device has the potential to capture surface geometry with an accuracy of 1-2 mm and currently measures distances between relevant orthopedic positions with an average error of only ±2.6% in first exemplary tests. Material hardness of objects with shore hardness 00-10, 00-20, 00-30 and 00-50, which is a realistic range for human tissue hardness, can be reliably differentiated.

Future research and development will prioritize refining sensor calibration and synchronization to enhance data quality, while improving the overall usability of the final sentence-glove product. This includes utilizing durable materials, adhering to hygienic design principles, and developing advanced algorithms for tissue-specific hardness assessment.

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