Investigation of Microwave Imaging Scanning Compared to Conventional 3D Laser Scanning for Capturing Body Dimensions Through Clothing

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Abstract

Capturing accurate body dimensions is crucial for the apparel industry, particularly in the creation of customized garments and ensuring an optimal fit. The current standard methods include using measuring tapes on key body areas or employing 3D scanners. Both techniques require the individual to wear tightly fitted clothing or no clothing at all to ensure accurate measurements. These inconveniences may be alleviated with so-called Microwave Imaging (MI), a lesser known imaging technology typically employed in security scanning. MI offers an alternative approach as it is capable of capturing body dimensions accurately and rapidly even under clothing. In this inital work, MI is thoroughly investigated and compared both visually and quantitatively to established measurement techniques. For a quantitative assessment, approximate methods for determining human body dimensions based on MI are presented and compared to aforementioned conventional measurements methods. All scanning procedures were conducted on a static mannequin, being tested in two distinct configurations: unclothed and wearing a jacket. The experimental setup is designed to evaluate the effectiveness of capturing body dimensions in general, and in particular through clothing, with a specific focus on exploring the potential applications of MI data in the context of body measurement.
To this end, MI demonstrates to be a fast, comfortable and feasible method for measuring body circumferences, rendering it a viable option for use in the clothing industry. The technology shows promise, especially in its ability to capture body dimensions even through thick clothing.

Keywords: Microwave Imaging, 3D Laser Scanning, Body Measurement

1. Introduction

The capture of body-specific data plays a central role in the development of clothing, as it significantly impacts fit, functionality, and comfort. In an era where the fashion industry is increasingly focused on personalisation and precision, accurate anthropometric data is crucial. A study by McKinsey and Company highlights that 71 percent of consumers prefer customised products, and 25 percent of fashion companies are already investing in mass customisation technologies [1]. Proper fit influences not only the aesthetic appearance but also the freedom of movement and overall well-being of the wearer. Traditional sizing systems, based on average values, often fail to address the diverse body shapes and sizes prevalent in a globalized society, leading to fit issues, dissatisfaction, and higher return rates.
Moreover, precise measurement of individual body dimensions enables the creation of functional clothing tailored to specific needs, such as in sports or work wear. Optimising ergonomic aspects and supporting natural movement sequences can greatly enhance garment functionality. The integration of advanced technologies like 3D scanning and artificial intelligence into the design and manufacturing processes allows for detailed and accurate body data capture, which can be efficiently used in production. According to Allied Market Research, the market for 3D scanning technology is projected to reach USD 5.7 billion by 2026, reflecting the growing significance of this technology [2]. This advancement not only improves customer satisfaction but also promotes sustainability by reducing material waste and overproduction.

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However, traditional 3D scanning methods require individuals to be undressed for accurate measurement, which many individuals may find uncomfortable or undesirable. This limitation underscores the need for alternative methods that can capture body geometry accurately while the subject is clothed. Microwave Imaging is a non-invasive imaging technology, commonly used to detect hidden or embedded objects, and a potential contender to alleviate these limitations. It operates by emitting electromagnetic waves in the microwave range of 300 MHz - 300 GHz, that can penetrate certain materials and are reflected off surfaces like skin and metals. The reflected waves are then captured by antennas to con- vert the received energy to digital data. Typical applications are security scanners at public facilities to find concealed contraband. In contrast to other methods that use electromagnetic waves, such as ultrasound or X-ray, MI is contactless and harmless [3, 4]. This technology could potentially address the discomfort associated with disrobing for measurements and offer a new approach to body dimension capture in the clothing industry. This paper aims to investigate the accuracy and potential of Microwave Imaging as a viable alternative to traditional 3D scanning technologies. MI data is compared with 3D laser scanning to evaluate how well MI performs in capturing body geometry accurately and how it might be utilised effectively in the apparel industry.

2. State of the Art Technologies for Capturing Body Dimensions

The precise recording of body measurements is a crucial component in the development of well-fitting and customised clothing, as well as in assigning a clothing size to the body geometry. Conventional methods for recording body measurements are based on manual techniques, i.e. measuring with a measuring tape.

Another technology is 3D scanning, which has become increasingly important due to its ability to take detailed and precise measurements of body shapes. These systems have become popular in various industries, such as fashion and healthcare, as they streamline the measurement process and improve fit accuracy. Mobile applications use smartphone cameras and advanced algorithms to provide convenient and accessible measurement solutions and further democratise the process of capturing body measurements. The following sections describe these technologies and sizing systems for clothing.

2.1. 3D Laser Scanning

3D laser scanning captures the surface of an object by emitting non-visible light, which is reflected off the object's surface and detected by the scanner. This process generates a point cloud, representing the scanned surface in fine detail. The entire surface of the object can be captured by positioning multiple cameras around it or by using a handheld scanner to move around the object as shown in Figure 1. Advanced 3D laser scanning technologies, such as the Artec Leo 3D scanner by ArtecStudio, offer resolutions as high as 0.01 mm, ensuring precise representation of surface structures and dimensions. The resulting point cloud is subsequently processed into a mesh using software like ArtecStudio [5] or MeshLab [6].

Fig. 1. Handheld Scanner Artec Leo [7].

The objects scanned can be either human or non-human. The focus here is on the application of 3D scanning for the human body. A 3D scan of a human body provides detailed information about body dimensions, which is crucial in the clothing industry, particularly for selecting correctly fitted garment sizes. For accurate clothing fitting, precise body measurements are essential, as any inaccuracies can lead to incorrect size recommendations (Section 2.2). To obtain accurate measurements, it is necessary to scan the body with minimal and close fitting clothing, as garments can distort the measurements. Tight-fitting, thin clothing is required during scanning to minimise interference. However, this can be problematic for some individuals who may feel uncomfortable being scanned in tight-fitting clothing.[8]

2.2. Clothing Sizing System

Traditionally, ready-to-wear sizes are assigned on the basis of body measurements collected by various measurement methods, such as manual measurements with a tape or by 3D laser scanning. For definition of the primary measurements the European standard EN 13402 is widely used [9]. It should be noted that these measurements, which include length and width measurements for ready-to-wear sizes, vary depending on the pattern system, country of origin and manufacturer. The differences between the measurements from one size to the next gradation, are referred to as 'grade rules'. In the M. Müller und Sohn pattern system, the measurements for ready-to-wear sizes, including the grade rules, are shown in the following Table 1 for male pattern sizing [10].

Table 1. Male Clothing pattern sizing table [10].

Size	44	46	48	50	52	54	56	58	60
Body height	1680	1710	1740	1770	1800	1820	1840	1860	1880
grading value		30	30	30	30	20	20	20	20
Chest circ	880	920	960	1000	1040	1080	1120	1160	1200
grading value		40	40	40	40	40	40	40	40
Waist circ	780	820	860	900	940	980	1040	1100	1160
grading value		40	40	40	40	40	60	60	60
Hip circ	900	940	980	1020	1060	1100	1160	1200	1240
grading value		40	40	40	40	40	60	40	40

Especially for the waist circumference - the primary measurement for the allocation of garment sizes for the lower body - the grade rules are typically 3-4 cm. This means that a measurement inaccuracy of more than 1.5 cm could result in the wrong size being assigned, especially in the smaller sizes, where the differences are smaller than in the larger sizes. Inaccurate body measurements therefore lead to inadequate fits, which emphasizes the importance of using precise scanning technologies. The accuracy of the body geometry measurement is crucial for the correct determination of the garment size. The same applies with clothing for the upper body. Here, the grading values for upper body measurements are 4 cm in standard sizes, so a deviation of 2 cm in the measurement would already lead to an incorrect clothing size. It is therefore of the utmost importance to ensure a high level of accuracy when measuring and scanning a body in order to guarantee a correct fit. The precision of these measurements is crucial for the correct determination of the garment size, thus avoiding fit problems and improving the overall quality of the garment. [11, 12, 13]

3. Microwave Imaging

Microwave Imaging is a technology derived from radar imaging and typically used in applications which require unique see-through capabilities. It leverages electromagnetic waves within a frequency range of 300 MHz to 300 GHz which travel through certain material and interact with underlying matter, ultimately capable of revealing internal structures. Unlike X-ray, whose high energy photons can ionize organic matter, making it potentially hazardous to living organisms, MI is non-ionizing and safe to use. It specifically enables contactless inspection of materials while being non-invasive to human skin, which makes it a safe alternative for body scanning purposes. Microwave Imaging has found widespread applications in various fields, including biomedical imaging [3], subsurface prospection [4], and security screening. In the context of security, microwave imaging is often employed to detect concealed contraband on individuals.

This study relies on MI technology from Rohde & Schwarz GmbH & Co. KG, operating in a frequency range that enables the acquisition of MI data at a lateral resolution of less than 2mm. The technology comprises two parallel flat MI panels between which the scanned individual is positioned. These panels are equipped with a large number of transmitter and receiver antennas. The transmitter antennas emit electromagnetic waves, which penetrate the clothing worn by the individual and are reflected by any objects or the skin. The receiver antennas capture the reflected waves, and advanced algorithms are applied to process the data to generate a microwave image in the form of a 3D volume. This process is illustrated in Figure 2.

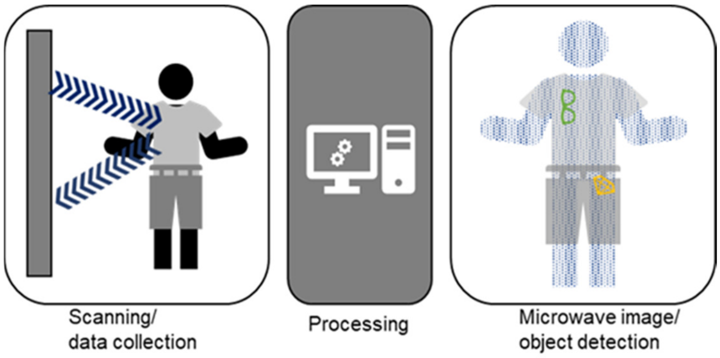


Fig. 2. Microwave Imaging person screening process.

4. Methods

This work explores the application of Microwave Imaging specifically for body measurement at the example of a static mannequin. To assess its feasibility, it is compared both qualitatively and quantitatively to established measurement paradigms, i.e. tape measurements and 3D laser scans. For a visual comparison, a 3D laser scan of a mannequin is registered to a corresponding MI volume of the same and their spatial correspondence is analysed. Furthermore, a quantitative analysis is conducted by measuring and comparing relevant circumferences of the physical mannequin with those obtained from both the 3D laser scan and the MI volume.

4.1. Experimental Setup

For the acquisition of the 3D surface data, an Artec Leo handheld scanner [7] was employed. This scanner provides a 3D accuracy of up to 0.1 mm + 0.3 mm/m over distance. With a data acquisition speed of up to 35 million points per second, it enables rapid and precise capture of complex geometries. The tex- ture resolution is 2.3 megapixels, and the 3D mesh output is available in various file formats, including OBJ, PLY, WRL, STL, AOP, ASC, PTX, E57, and XYZRGB. To acquire the MI data, MI technology from Rohde & Schwarz GmbH & Co. KG [14] was used. This scanner operates in the frequency range of 70 GHz to 80 GHz and utilises a multistatic approach with thousands of transmit and receive antennas per panel. The transmit power is approximately 1 mW, and the data acquisition time is around 32 ms per panel. A mannequin in a fixed pose serves as a model for human anatomy and constitutes the test subject for the subsequently described experiments. The static pose of the mannequin facilitates comparability and accurate registration between different scans and scanning techniques.

First, the mannequin was placed in the MI scanner and a 3D MI volume was acquired. Afterwards, the same mannequin was scanned using the Artec Leo 3D scanner to obtain a corresponding 3D laser scan. The mannequin was not moved in-between. Subsequently, the mannequin was clothed with a jacket with the objective to demonstrate the effectiveness and accuracy of MI in the extraction of actual body geometry through clothing. For the experiments, the use of a mannequin is crucial to ensure the highest possible pose equality and alignment of the captured data. The jacket used for the experiment is a typical work wear jacket with many pockets, layers and a lining. In the MI scan of the mannequin with jacket (see Figure 3 C), the right chest pocket made of PTFE is visible, since the electromagnetic waves are reflected off that material and cannot penetrate it.

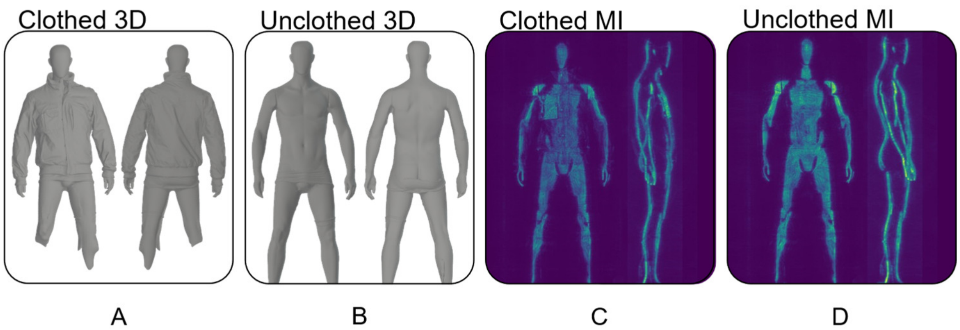


Fig. 3. Data retrieved by the Artec Leo 3D scanner (A, B) as 3D objects and MI (C, D) as maximum intensity projections of the 3D volume. Scans were taken of a mannequin wearing a jacket (A, C) and without clothing, except for a hip bandage (B, D).

The raw data of the 3D scan is in Artec's proprietary file format and must first be imported into the Artec Studio 18 software. In this software, the data is processed, including tasks such as closing holes and optimizing surfaces. The processed data is then exported as an OBJ file [5]. Subsequently, the MI volume and 3D scan data are manually aligned with each other to perform a visual comparison. Furthermore, body dimensions are measured based on both the 3D scan and the MI volume, as described in the following sections. The comprehensive process and methodologies employed in this study are depicted in Figure 4.

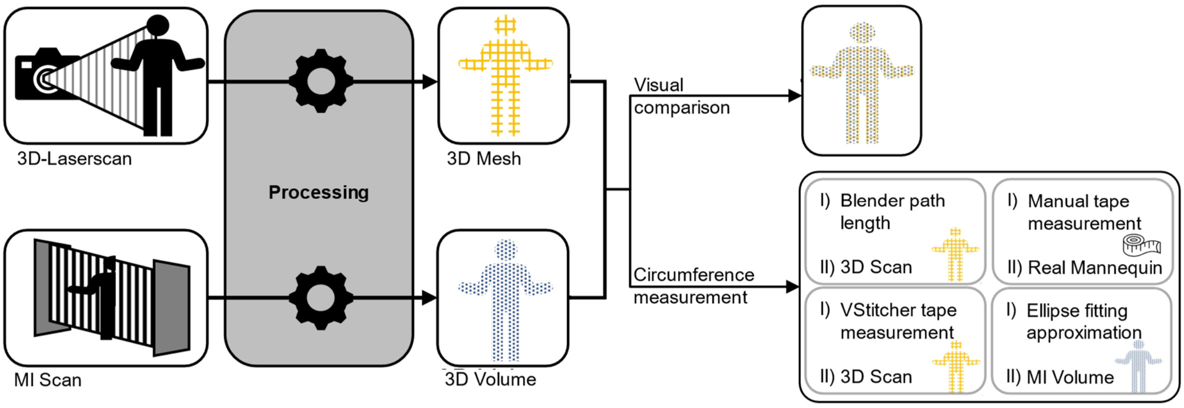


Fig. 4. Illustration of the process of this study. The 3D scan and MI data are first acquired and processed. Subsequently, the data is aligned for visual comparison, and body measurements based on circumference measurement methods (I) are applied to both data types (II).

4.2. Visual Comparison

Main For a qualitative assessment, i.e. a visual comparison, the MI volume and 3D laser scan were first precisely aligned and then displayed in ParaView [15]. Subsequently, three cross-sectional slices were extracted at three different positions particularly relevant to clothing technology, i.e. along the bust line, midsection, and hip, as illustrated in Figure 5. The Figure shows i) the aligned 3D laser scans of the mannequin with and without a jacket in lower opacity, as well as ii) the surface path of the three slices from both 3D laser scans and iii) the corresponding slices from the MI volume. Note that the mannequin's arms had to be re-positioned slightly when putting on the jacket, resulting in a shift of the arms and hip/legs between the scans with and without the jacket. To accommodate for this, the data was aligned based on the stationary body parts, specifically the head and torso. For the visualization in Figure 5, the MI scan of the mannequin without clothing was used, as the alignment of the MI scan with clothing would have been considerably more intricate. A more detailed, visual comparison of the MI scans of the mannequin both with and without clothing is provided in Section 4.3.

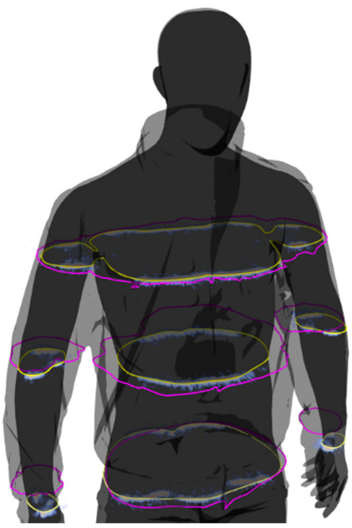


Fig. 5. Alignment of the 3D scan of the mannequin with and without jacket and the MI scan of it without clothes. The 3D scan of the mannequin with jacket is illustrated with a lower opacity than the one without jacket.

4.3. Body Measurement

For a quantitative assessment of the different methods, the mannequin's chest, waist and hip circumference were measured physically with a measuring tape, and computationally using the 3D laser scan and an MI scan, respectively. The resulting circumference values were then mapped to Table 1 to determine the respective clothing size.

Tape measurement: Tape measurement is the traditional way of measuring body parts, specifically body circumferences. However, this method tends to bridge over small depressions, such as e.g. the curve of the spine, rather than following the true contours of the body. Using the measuring tape, the physical circumferences at the three positions were first recorded by hand, to obtain reference values.

3D scan path length: To computationally determine the path length of the mannequins circumferences from the 3D laser scan, the data was imported into the open-source software Blender [16], where precise measurements were obtained. By positioning three axial planes at corresponding heights of chest, waist, and hip, the intersecting area between the 3D laser scan and the planes was extracted using a Boolean modifier. Subsequently, the path length of the circumferences of the resulting intersections could be measured.

Virtual tape measurement: The circumferences of the 3D scan were also measured digitally using VStitcher from Browzwear [17]. The software's 'tape measurement' functionality simulates the behavior of a physical measuring tape and is applied to user-defined set points. Consequently, varying the placement of these set points can influence the measurement outcome, as the functionality follows the path around the object.

MI scan circumference approximation: To ensure consistency, the measurement heights of the 3D scan were recorded to measure the circumferences in the MI data at identical heights. For obtaining measurements from the MI data, a custom graphical user interface (GUI) was developed, as none of the available tools were able to cope with the data at the time of writing. The custom GUI allows the user to navigate through axial cross-sections from the 3D MI volume, visualising each slice as a 2D image. The heights in the MI volume as well as the corresponding slices are illustrated in Figure 6. The user can place points in the MI slice to form a path on the image, which are subsequently used to fit an ellipse, assuming an ellipsoid approximation of the body part's circumference (see Figure 7).

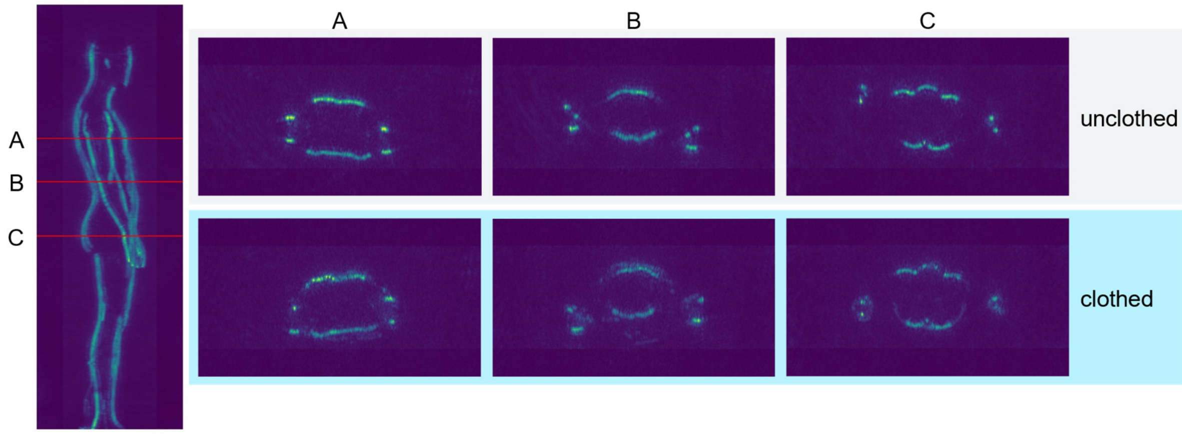


Fig. 6. 2D slices of the MI volume of the mannequin, corresponding to the A) chest, B) waist, and C) hip regions, are presented for two scenarios: I) measurements taken without clothing and II) measurements taken with a jacket.

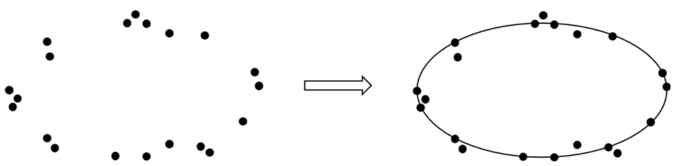
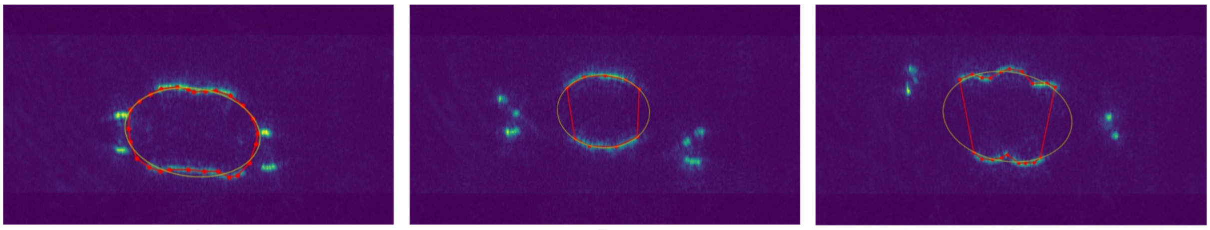


Fig. 7. Illustration of fitting a 2D ellipse to a given set of points.

The Total Least Squares (TLS) estimator is used to fit a two-dimensional ellipse to the manually set points. The TLS estimator minimizes the sum of squared orthogonal distances from the data points to the ellipse, which can be formulated as a quadratic minimization problem. This yields the optimal ellipse parameters (center, axes lengths and orientation). In the GUI, the TLS estimator is applied to the manually set points upon user command. Examples of those points and the resulting ellipses for slices of the MI volume at chest, waist, and hip positions are shown in Figure 8. The illustrated slices are derived from the MI volume of the unclothed mannequin. In Figure 8 A, the arms help in projecting the chest path on both the right and left torso sides, enabling the accurate placement of points along the entire path. In contrast, Figures 8 B and C exhibit areas with reduced illumination. Combined with a greater distance to the arms, this makes it hard to place points in those areas without resorting to estimation. Consequently, points for both waist and hip (Figure 8 B and C) were only set in areas with sufficient illumination, where confident placement and accurate tracing of the scanned body's surface is possible. Despite this limitation, it was still possible to obtain a reliable fit of an ellipse to the set points.



A B C

Fig. 8. Axial cross-sectional slices of the MI volume of the mannequin without clothes at A) chest, B) waist, and C) hip positions.

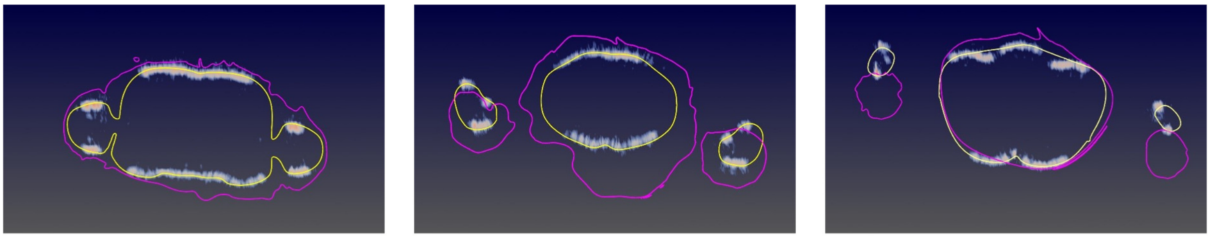
After fitting the ellipse, the GUI displays the actual path length between the manually chosen points as well as the circumference of the fitted ellipse and stores these values for further analysis. In Section 5, the measurements are compared to all previously mentioned body measurement methods. Additionally, all measurements are correlated with corresponding clothing sizes, providing a practical evaluation of the results.
All measurements, with the exception of the measurement performed in Blender, were repeated five times. The average value and standard deviation were then calculated for each measurement set, providing a quantitative assessment of the measurement variability and reliability.

5. Results

In the following, the visual comparison described in Section 4.2 and the quantitative, comparative analysis of different methods as per Section 4.3 are presented.

5.1. Visual Comparison

The cross-sectional slices, previously shown in Figure 5, have been extracted and are presented as 2D images in Figure 9, illustrating the A) chest, B) waist, and C) hip regions. Specifically, the circumference of the 3D scan of the clothed mannequin is depicted in purple, the circumference of unclothed mannequin in yellow, and the grayscale intensity values represent the MI data of the mannequin (without clothing). The high intensities represent the captured surface of the mannequin, off which the electro- magnetic waves are reflected.
The illustration demonstrates that the MI volume, in particular the captured surface, accurately over-lays with the surface of the 3D laser scan, indicating that MI can capture the surface of the mannequin at a level of precision similar to 3D laser scanning (see the white and yellow lines in 9 A) and B)). In slice 9 C), a slight mismatch is observed between the MI data (grayscale) and the 3D laser scan (yellow outline), which is attributed to a bandage covering the front part of the hip region of the mannequin where measurements were taken (refer to Figure 3). This discrepancy itself already highlights the effectiveness of MI in capturing body surfaces through clothing. Notably, the MI grayscale intensities follow the contours of the body, while the yellow outline lies above those contours, illustrating that 3D laser scanning is limited in capturing precise body surfaces when clothing is worn. The purple lines in all images demonstrate the same limitation. It is worth noting that the purple line in Figure 8 C) does not align with the other data. This discrepancy is attributed to the movement of the mannequin that occurred when the jacket was put on, resulting in a rotation of the hip and arms with respect to the torso.



A B C

Fig. 9. Circumferences of cross-sectional slices from the 3D scan of the mannequin with jacket (purple) and without clothing (yellow), compared to cross-section of the MI volume of the mannequin without clothes (white) at A) chest, B) waist, and C) hip position.

Furthermore, a visual comparison of the MI scans of the clothed and unclothed mannequin is presented. Figure 6 illustrates the axial planes at the three regions of interest, with the upper row depicting the slices without clothes and the lower row showing the slices with the jacket on. Noteworthy, the mannequin was moved during the clothing process, resulting in a rotation and positional shift of the data, causing the two scans to not align. Apart from some additional noise introduced by the jacket, it is evident that the body surface is captured with similar precision with and without clothing.
A small mismatch is visible on the left side of the chest, which is attributed to the material of the chest pocket. Notably, even with the work-wear jacket, the body dimensions can be accurately captured, indicating that MI may be a promising alternative for body measurement purposes, even through thick clothing materials.

2.7. Circumference Measurements

For a quantitative assessment, four distinct methods for body circumference measurement are employed and compared: path measurement in Blender, manual measurements using a measuring tape, GUI-based MI circumference approximation through ellipse fitting, and 'tape measurement' of 3D laser scans using VStitcher, as per Section 4.3. To determine the reliability of the results, the last three methods were repeated five times, and the average value and standard deviation were calculated. The results of the respective circumference measurements of the mannequin without clothes are presented in Table 2. The Table reports the measured circumference statistics for the chest, waist, and hip measurements of the mannequin, as well as the corresponding ready-to-wear size, determined according to the sizing system measurement guidelines outlined in Table 1 [10].

Table 2. Circumference measurements comparison of the mannequin without clothing. The 'real path length' refers to the measurement obtained using Blender.

	real path length in [mm]	Measuring Tape		MI Scan		3D Scan	
		circ in [mm]	cloth size	circ in [mm]	cloth size	circ in [mm]	cloth size
Chest	1044	1021.7 ± 3.1	52	1051.5 ± 8.6	52	1011.5 ± 7.3	50
Waist	809	800.0 ± 1.1	46	793.5 ± 5.9	44	795.0 ± 1.6	44
Hip	1032	1029.6 ± 2.7	50	1030.1 ± 7.4	50	1026.9 ± 9.8	50

The real path length measured using Blender is on average consistently higher than the average manual measurement obtained with a measuring tape. This discrepancy is likely attributed to the fact that the measuring tape does not account for the body's natural contours, such as dents and irregularities, which are accurately captured by the Blender measurement. The comparison of the chest circumference results reveals that the measurement based on the MI scan accurately corresponds to the same clothing size, i.e. size 52 as the manual tape measurement, while the 3D scan measurement indicates a smaller clothing size, i.e. size 50. The measurements based on the MI scan, which approximate the circumference with an ellipse, are on average 30 mm wider than the manual tape measurement. In contrast, the 3D scan measurement is only 10 mm smaller than the manual tape measurement. Al- though the MI scan measurement corresponds to the same clothing size as the manual measurement, the virtual tape measurement of the 3D scan is actually closer to the manually measured value. The relatively large difference between the MI scan measurement and the manual measurement may be attributed to the ellipse fitting method. Specifically, the contour of the chest more closely resembles a rectangular shape with soft edges, rather than a perfect ellipse.

For the circumference of the waist, the manually determined clothing size is one size larger (size 46) compared to the size assigned to the circumference values of the MI and 3D scan (size 44). However, the actual differences between all the measurements are relatively small, with an average difference of 5 mm between the measuring tape and 3D scan, and a 6.5 mm difference between the tape and MI scan. Notably, the grading value limit for assigning the clothing size is exactly 800 mm, which highlights the sensitivity of the clothing size classification to small measurement variations.
For the hips, the circumference measurements are in average very similar for all methods. More precisely, MI and tape measurement are nearly identical, and 3D laser scan measurement shows a mean result 3 mm less in circumference. Consequently, all three methods yield the same clothing size assignment. Notably, despite the hip shape deviating from a typical ellipsoidal shape, the ellipsoid approximation employed in the MI scan still produces remarkably accurate results.
Overall, a comparison of the measurement methods reveals that, when considering the manual measurement with tape as a reference, the 3D laser scan achieves more accurate circumference values for the chest and waist regions, while the MI scan circumference value is closer to the manual tape measurement around the hip area. Furthermore, the results suggest that fitting an ellipse to manually set points in axial planes of the MI volume constitutes a viable approximation for both the waist and hip regions. Undisputably, this approximation is less suitable for the chest area. It is essential to acknowledge that there is no absolute ground truth, as each measurement method is subject to its own inherent flaws and deviations. Therefore, the comparison of measurement methods should be interpreted as a relative evaluation of their accuracy and reliability, rather than an absolute assessment against a true reference value.

5.3. MI Scan through Clothing

As discussed in Section 3, MI technology has the capability to capture body geometry through clothing. To evaluate how the accuracy of measurements obtained through clothing deviates from scans without clothing, the mannequin was scanned with a lined jacket and compared to an undressed scan. The results of this comparison are presented in Table 3, which were again obtained using the ellipse fitting method applied to the MI volumes.

Table 3. Chest, waist and hip circumferences determined from MI scanning with and without clothing via ellipsoid fitting.

	unclothed		clothed	
	circ in [mm]	clothing size	circ in [mm]	clothing size
Chest	1051.5 ± 8.6	52	1061.7 ± 15.6	54
Waist	793.5 ± 5.9	44	790.2 ± 10.8	44
Hip	1030.1 ± 7.4	50	1044.9 ± 13.5	52

The comparison of the measured circumferences reveals that the values are similar, even when the body geometry is recorded through clothing, but not identical. More specifically, the average chest circumference of the scan data with the jacket is in average 10 mm wider, resulting in a larger clothing size (size 52 vs size 54) according to Table 1. In turn, at the waist, the mean value is 3 mm smaller than the circumference of the mannequin scanned without the lined jacket. The average hip circumference is in average 14 mm wider in the presence of clothing, also leading to a slightly larger clothing size assignment for the clothed mannequin (size 50 vs size 52).
It is unclear what these fluctuations in circumference measurements from clothed MI scans can be attributed to. The observed deviations from the measurements of the unclothed mannequin may be influenced by the limited number of repeated measurements (5 per position), induced by clothing-induced noise and artifacts, or shortcomings of the approximating ellipse fitting approach itself. However, for all.
the different measurement positions it is evident from Table 3 that circumference measurement variance with clothed MI scans is approximately double the variance of unclothed scans. Despite the noticeable differences, the results demonstrate MI's capability to effectively extract circumference measurements in the presence of heavy clothing.
In light of the observation that the chest resembles a rounded rectangle rather than an ellipsoid, the actual path lengths formed by the manually placed seed points in the GUI for body measurement in MI are presented in Table 4.

Notably, while these points were only placed on the illuminated areas for both waist and hip, they were placed along the entire chest surface visible in the MI scan. Consistent with our observation that the body shape does not closely resemble an ellipsoid, the actual path length is found to be closest to the manual measurements with the tape. In contrast to the chest area, the assumption of a rounded rectangular shape does not hold for the waist and hip circumferences, as these regions exhibit a more elliptical body geometry.

Table 4. Chest, waist and hip circumferences determined from MI volumes with and without clothing via semi-automatic path-length estimation versus manual tape measurement.

	Measurement Tape in [mm]	unclothed path in [mm]	clothed path in [mm]
Chest	1021.7 ± 3.1	1029.5 ± 6.6	1047.5 ± 16.5
Waist	800.0 ± 1.1	722.6 ± 11.8	718.3± 15.9
Hip	1029.6 ± 2.7	958.6± 6.7	1007.6 ± 9.3

6. Discussion

The analysis presented in Section 5 yields several key insights into the effectiveness of Microwave Imaging for body measurement compared to conventional 3D scanning technologies, particularly in scenarios where clothing may obscure body anatomy.

The visual comparison demonstrates that MI technology excels in penetrating through clothing, as evident from the clear depiction of body dimensions despite the presence of a work-wear jacket. This capability highlights a significant advantage of MI over conventional 3D scanning, which typically requires the subject to be unclothed or wear minimal, tight-fitting clothing for accurate measurements.

The MI scan's ability to capture body geometry through fabric without significant loss of detail is a notable strength, particularly in applications where privacy or comfort concerns may prevent disrobing. Thus, the ability of MI to accurately depict the body's contours beneath the clothing suggests that it can be a valuable tool in the apparel industry, where precise body measurements are crucial for garment fitting and correct sizing assignment.

The evaluation of body circumference measurements — specifically chest, waist, and hip circumferences — demonstrates that MI technology presents a promising alternative for body measurement, even when assuming an elliptical approximation of the circumference. The deviations in the measured circumferences demonstrate that MI is able to achieve a level of body measurement accuracy comparable to conventional 3D scanning for the selected body parts. Both measurement techniques correctly assigned two out of three clothing sizes. It is noteworthy that even small measurement deviations of a few millimeters can result in incorrect clothing size assignments. This is particularly significant given that conventional 3D scanning often requires subjects to be unclothed, limiting its practicality. In contrast, MI effectively captures body geometry through clothing, offering a robust solution for garment fitting and customization in scenarios where 3D scanning is impractical or entirely unfeasible. Overall, MI's capability to accurately measure body dimensions through clothing highlights its suitability for applications where maintaining comfort and accessibility is essential.

Table 5 summarises the characteristics and advantages and disadvantages of the two systems compared.

7. Conclusion

In summary, this initial work reveals that MI technology holds the potential to present an alternative to conventional 3D scanning, particularly in contexts where clothing is a factor. Its ability to capture body dimensions through clothing and to accurately reflect body geometry may render it a valuable tool in garment fitting and customization. Especially the visibility of air gaps between the mannequin and the jacket in the MI scan show its capacity to discern between the body and the clothing. This feature may allow for a more nuanced understanding of how clothing affects fit and shape, which can be particularly useful for designing garments that accommodate various body shapes and sizes. This opens up interesting opportunities for investigations in the field of firefighter clothing, as the air gaps between clothing and the human body are decisive for the possible dwell time in heat. However, while MI demonstrates significant advantages, the effectiveness of MI in capturing body geometry through clothing may also be influenced by the thickness and material of the fabric from special work wear. To this end, this work has focused on selected body measurement scenarios around the chest, waist and hip. An extension to wider areas of the anatomy and subsequent investigations are required. Further studies are needed to evaluate how different types of clothing and fabric densities impact the accuracy of MI measurements. Future work may also focus on exploring MI's technology integration with other output data formats for more accessible measurement methods in conventional CAD programs to maximize its potential in the apparel industry. There is also potential for a variety of follow-up work in the reals of MI itself. The MI image resolution and imaging concept may further be enhanced to cater more explicitly to body measurement applications through different reconstruction parameterisations and methods. Further, the ellipse fitting heuristics used in this study just constitutes a rough approximation and may obscure a measurement accuracy which in reality might be much higher. To address this, elaborate surface extraction algorithms for MI need to be developed to turn high-resolution MI data into 3D avatars.

Overall, this feasibility study proved to be successful and highlights the potential of using high-resolution MI scanning for applications in the clothing industry. Particularly in scenarios where clothing is worn, the current limitations of 3D laser scanning in measuring the body geometry may be bridged by MI scanning.

Table 5. Comparison of the discussed scanning systems.

Criteria	3D Laser Scanning	Microwave Imaging
Measurement accuracy	High precision for surface capture	High precision, even through clothing
Sensitive to lighting conditions	Sensitive	Robust
Suitability for clothed subjects	Limited; usually requires unclothed subjects, scans only outer surface	Excellent; can scan through clothing
Capture range	Surface measurement	Captures both surface and body geometry
Required preparations	Minimal, but often requires un-dressing	No need to change clothes
Material penetration	Limited to surface	Can penetrate various materials (clothing)
Data processing	Produces detailed 3D mesh surface models	Produces volume data (by default)
User-friendliness	Easy to use, but requires specialized software	Simple, but currently requires specific data interpretation
Data acquisition time	Relatively quick, depending on scanner technology	Usually quick, also in seconds
Challenges	Requires good lighting and/or special scanning conditions	Influenced by material density and composition if subject is clothed
Portability	Yes, if handheld system	No

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