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**Evaluating the Accuracy of Low-Cost Scanning Technology to Reconstruct Full Body
Morphology**

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Abstract

Accurate reconstruction of full-body morphology is critical in many fields. This study evaluated the accuracy of three low-cost scanning technologies for capturing 3D body surface geometry: LiDAR sensors, ZOZOSUIT2 and ZOZO_v3. Participants were scanned using laser scan, LiDAR, and ZOZO's methods. The scans were fitted to STAR models for comparison. The low-cost technologies captured 3D body surface geometry in an adult population, with RMSE values of 11.33 ± 4.39 mm (LiDAR), 7.13 ± 1.65 mm (ZOZOSUIT2) and 6.61 ± 1.93 mm (ZOZO_v3). All three methods demonstrated no gender bias in reconstruction accuracy.

Keywords: 3D body scanning, LiDAR, ZOZOSUIT, body surface geometry, anthropometry

Word Count: 4302 words

Introduction

Subject-specific and accurate reconstruction of full-body morphology is a critical aspect in numerous fields, including ergonomics, anthropometric measurement, design research, sports science, and clinical applications ¹⁻⁴. Although high-precision three-dimensional (3D) scanning technologies have been employed to achieve these goals, their high cost and limited accessibility often hinder widespread adoption. Over the past few decades, the market has seen a proliferation of 3D scanners that offer high repeatability and rapid scanning times, making them more accessible and practical for various applications ⁵. This evolution in 3D scanning technology holds promise for broader implementation across diverse disciplines, driving innovation and improving outcomes. The interest in low-cost technology, such as LiDAR scanners and stereophotogrammetry, for reconstructing biomechanical models that can be deployed in clinical settings is increasing. One challenge of low-cost scanning technology is the resulting sparse and noisy point clouds compared to more expensive 3D body laser scanners ^{6,7}.

The LiDAR technology implemented in consumer devices such as iPads and iPhones has made this technology accessible to everyone. LiDAR technology captures a detailed point cloud by measuring the time taken for emitted light pulses to return. While it provides accurate distance measurements, it struggles with capturing surface textures and fine details, particularly in human features ⁸. Studies have explored LiDAR's potential in various fields, including sports, horse riding, and forensics, with findings indicating high accuracy in linear body measurements ⁹⁻¹². However, research has primarily focused on linear dimensions rather than full 3D body scans, necessitating further investigation into LiDAR's ability to reconstruct body surface geometry. In archaeological and museum studies, comparisons between high-end and consumer-grade LiDAR sensors have shown varying success depending on the scanning application and object size ¹³. While Polycam has proven to be the most reliable overall, free

apps like Scaniverse show promise for capturing different volumes ¹³. These findings suggest that while LiDAR has potential for 3D body scanning, further research is needed to assess its accuracy beyond linear measurements.

Stereophotogrammetry, an alternative to LiDAR, reconstructs 3D structures from multiple images. ZOZO Inc. (Chiba, Japan) employs this technique, with or without the calibrated ZOZOSUIT2 for personalised clothing fit. A study comparing a suited mannequin to the Artec EVA scanner found a low mean surface-to-surface error of 3.83 mm ¹⁴. However, as the study was limited to a single stationary mannequin, it is uncertain whether the same results would hold if tested on a human. While ZOZO offers a convenient method for capturing body morphology, its suitability for accurate 3D surface scanning requires further validation. Validation is essential for assessing 3D body scanning accuracy. Among available methods, 3D body laser scanners are the reference standard, showing good to excellent reliability compared to manual anthropometry ^{15–20} and serving as benchmarks for low-cost alternatives ²¹. A key challenge in validation is ensuring the participant maintains the same pose between scans, as movement introduces external errors. This can be mitigated by fitting a statistical shape model (SSM) to the point clouds and standardising the pose. Two freely available body SSMs exist: the widely used Skinned Multi-Person Linear model (SMPL) ²² and the more recent Sparse Trained Articulated Human Body Regressor (STAR) ²³, which improves skin deformation and accounts for sex-based shape differences. Only one study has used the SMPL model to scale participant skeletons with LiDAR for musculoskeletal modelling ²⁴; however, the quality of the LiDAR scans was not evaluated. Despite the growing use of consumer-grade scanning technology, no study to date has evaluated how accurately parametric body models (such as STAR) can be fitted to laser scans or compared these fits against low-cost options like LiDAR and ZOZOSUIT2. This work fills this gap by leveraging the STAR model to eliminate subject position changes between scan, to provide standardised comparison framework.

This study aimed to assess the accuracy of two low-cost scanning technologies to capture 3D body surface geometry: the LiDAR sensor and the ZOZO App, with and without the ZOZOSUIT2. A STAR model was fitted to each resulting point cloud to remove any pose differences between scans and then translated to a standard T-pose for comparison. The study focused on three key objectives: (1) Understanding the error associated with STAR model fitting on the raw scan resulting point clouds, (2) Evaluating the accuracy of the STAR fitted LiDAR scan and ZOZO application (with and without suit) to a ground truth laser scan in a standard zero-pose, and (3) Evaluating if potential sex biases exist in the scanning and fitting reconstruction based on shape differences between males and females.

Methods

Participants

Thirty-five participants (15F – 20M; 28 ± 6 years; 73.65 ± 13.47 kg; 174.20 ± 8.87 cm) signed a consent form and underwent a laser scan. Thirty-four completed a LiDAR scan (14F – 20M), and twenty-nine (13F – 16M) completed a scan using the ZOZO App. Participants were grouped as follows: Group 1 ($n = 28$) completed all three scans, Group 2 ($n = 34$) completed laser and LiDAR, and Group 3 ($n = 29$) completed laser and ZOZO. The study was approved by the Auckland University of Technology Ethics Committee (approval number 20/282). Informed written consent was obtained prior to any data collection.

Data collection

Participants wore tight shorts, a head cap to contain their hair, and a sports bra for women, for laser and LiDAR scanning. A Vitus XXL (Human Solutions GmbH, Kaiserslautern, Germany) was used for the ground truth whole-body three-dimensional (3D) laser scan. An iPad Pro (2020, 11-inch, Apple Inc., Cupertino, USA) with an integrated LiDAR sensor, combined with the Scaniverse application (v. 1.9.3), was used for the LiDAR scans. Participants were sized to

a ZOZOSUIT2 before being scanned using the ZOZO app (ZOZO Inc., Chiba, Japan). All scans were performed on the same day.

Full body laser scanner: The 3D laser scanner projects non-ionising light onto the body, which is captured by cameras at a series of points (between 700,000 and 1,000,000), each with Cartesian coordinates. The points are stitched together to represent the body digitally, with a precision tolerance of < 1 mm. Participants stood on a box with their feet approximately 20 cm apart and arms abducted from their torso at 20-30 degrees. Participants held their breath for the 15 seconds scan.

LiDAR scanner: For the LiDAR scan, participants stood in the middle of a room, with a leg and arm position representative of that used in the laser scan and were discouraged from moving for the duration of the scan. The Scaniverse application has been used for scanning as after testing it was the best free application allowing full body scanning. The operator scanned around the participant from top to bottom, moving in a clockwise rotation, from a distance of 1 m, until reaching the starting position. Instantaneous scan feedback was visualised, and the scan was repeated if the outcome was unsatisfactory. No more than two attempts were required. The scan duration was approximately 2 minutes.

Zozosuit scanner: The ZOZOSUIT2 is a calibrated bodysuit with a smartphone application that measures body sizes for personalised clothing fit. The suit covers the whole body except the head, fingers and feet. It is available in multiple sizes and made from stretchable material to fit a wide range of body shapes. The suit is covered with approximately 20,000 fiducial markers. Each marker, with a diameter of 6 mm, can be identified by the application running on a smartphone or tablet equipped with a 4K camera. Participants stood in the middle of the room in the same position as the first two scans. The iPad was positioned 2 m from the participant on a table, ensuring the whole body of the participant was visible in the ZOZO app. The participant progressively rotated in a clockwise direction, stopping at each

30-degree increment. At each position, a discrete image was captured using the ZOZO app, resulting in a total of 12 images. The images were analysed within the app to extract the two-dimensional positions of each fiducial marker and the subject's silhouette. Starting with a generic parametric mesh, the fitting process is iteratively optimised to best match the shape and posture of the participant based on the 12 images, resulting in a 3D virtual human body model fitted with the SMPL statistical shape model ²². The app allowed reconstructions using its 'with suit' (referenced as ZOZOSUIT2 condition) and 'without suit' (referenced as ZOZO_v3) functions. Within our analysis, the same images were used in both post-processing methods: ZOZOSUIT2, which uses calibration from the suit, and ZOZO_v3, which does not. The scan duration was approximately 1 minute.

Data post-processing

The 3D scanner output files were either meshes: laser scan and ZOZO or point clouds: LiDAR scan (Figure 1). To account for variations in poses across the scans, the output files were fitted to the Sparse Articulated Human Body Regressor (STAR) model in Python (v3.10.14) ²³. Specifically, registration was performed using custom PyTorch and PyTorch3D-based optimisation framework. The target scans were first sampled into point clouds ($n = 200,000$ points). The fitting process iteratively estimated the optimal STAR shape (β), pose (θ), and global translation parameters by minimizing the point-to-mesh distance loss between the target scan point cloud and the generated STAR body mesh. This non-rigid optimisation was executed using the Adam optimiser (learning rate = 0.01) for 1000 iterations. To ensure robust convergence, the optimisation was staged, sequentially relaxing constraints on global translation, global rotation, limb articulation, and finally, body shape parameters. Custom initial poses constrained at the ankles, feet, neck, head, wrists, hands and shoulders were used to improve accuracy. For participants with fitting errors, additional constraints limited joint ranges. Hand orientation ('front' or 'side') was specified to adjust initial parameters. STAR also

allowed for sex specification, with female, male, and neutral model options. The STAR-fitted meshes were all resampled to 200,000 points (instead of the original 6,890).

The resulting STAR-fitted meshes (Figure 1) were then moved to a standard zero-pose (Figure 2), where all joint angles were set to 0. This standardised pose ensured precise comparisons across different devices.

The output from the ZOZO App was a SMPL-fitted mesh (Figure 1).

Data analysis

Fitting error calculations: Fitting error between each scanner's raw point cloud and the STAR fitted mesh (Figure 1) was computed by calculating a point-to-point distance error using a custom Python script with KDTree nearest-neighbour search, followed by root mean square error (RMSE) and mean average error (MAE) computation. Three accuracy metrics were computed per participant and scan: 1) full body (FB); 2) excluding head and hands (NHH); 3) further excluding feet (NHHF), to account for deformation at extremities in LiDAR scans. These three metrics are referred to as the fitting error methods. Node distance errors between raw scans and STAR-fitted meshes were visualised in CloudCompare²⁵. It should be noted that fitting errors for the ZOZOSUIT2 and ZOZO_v3 are not included in the results. The ZOZO App directly export SMPL mesh rather than a raw point cloud. The STAR model was therefore applied solely to convert the ZOZO mesh into a standard zero-pose for comparison. Computing a fitting error for this specific step was omitted, as fitting one parametric model to another introduces topological bias and cannot be fairly compared to the raw data fitting errors of the laser and LiDAR scanners.

Scanning methodology accuracy: In the second part of the analysis, the STAR-fitted meshes in the standard zero-pose (Figure 2) were used to assess the accuracy of the LiDAR, ZOZOSUIT2 and ZOZO_v3 STAR-fitted meshes, with the laser scan STAR-fitted mesh as ground truth. Point-to-point distance errors were computed using the same custom Python

script as for the fitting error. Scan volume differences were calculated with the Trimesh Python library, and volume percentage error was quantified as:

$$\text{volume percentage error} = \frac{|A - B|}{\frac{A + B}{2}} \times 100 \quad \text{Eq. (1)}$$

Where A is the reference (laser scan) volume and B is the compared method (LiDAR, ZOZOSUIT2 or ZOZO_v3). Total full body volume differences were computed first, then the body was segmented into left/right arms, upper/lower torso, and left/right legs (Figure 2), with segment-wise volume difference calculated using Eq. (1). Finally, the heights of the STAR-fitted meshes in standard zero-pose for laser scan, LiDAR, ZOZOSUIT2 and ZOZO_v3 were computed and compared against the manually measured height.

Node distance error maps between standard zero-pose scans (LiDAR-laser and ZOZOSUIT2 vs. laser and ZOZO_v3 vs. laser) were visualised in CloudCompare²⁵.

Sex differences analysis: The effect of sex on the scanning accuracy was analysed by comparing 1) the fitting errors for the laser scan and LiDAR scan, and 2) the scan method accuracy using the STAR-fitted meshes in the standard zero-pose position and comparing the laser scan with LiDAR, ZOZOSUIT2 and ZOZO_v3.

Statistical analysis: Statistical analyses were conducted using R (v4.4.1, R Core Team, 2024), and data series normality was assessed using the Shapiro-Wilk test. To evaluate the accuracy of the scanning method in the standard zero-pose condition, which involved three groups (LiDAR, ZOZOSUIT2 and ZOZO_v3), only participants who had performed the 3 scans (Group 1) were considered. The RMSEs were not normally distributed, so a Friedman test was conducted, followed by a post-hoc Wilcoxon signed-rank (pairwise) post-hoc test with the Bonferroni correction to account for multiple comparisons. The same analysis compared the full body volume between scanning modalities.

For sex comparisons involving two groups (male and female), Fisher's F-test was used to assess variance homogeneity. If variances were equal, a Student's t-test was performed; otherwise, a Welch's t-test was used. A Mann-Whitney U test was applied if the data were not normally distributed.

Results

Fitting error

The average full-body (FB) laser scan fitting RMSE was 6.18 ± 0.70 mm (MAE: 4.81 ± 0.48 mm), with values ranging from 4.94 mm to 7.97 mm (Figure 3, dot box). A reduction in RMSE was observed after removing the head and hands (NHH) from the fitting error calculation, with average RMSE values of 5.74 ± 0.70 mm. Further, removing the feet (NHHF) did not improve the fitting error, with an average RMSE of 5.78 ± 0.73 mm. The three conditions had only one outlier. Errors emerged predominantly around the hands and upper body for the participant with the lowest RMSE, and additionally in the pectoral region and inner thigh for the highest RMSE.

The average LiDAR scan fitting RMSE was 9.49 ± 1.18 mm (MAE: 7.84 ± 1.05 mm) for the FB condition (Figure 3, filled box), decreasing to 8.96 ± 1.13 mm after removing the head and hands, and further decreasing to 8.59 ± 1.20 mm after also eliminating the feet. Errors were relatively evenly distributed for the cases with the lowest and highest fitting errors. Anthropometric factors did not impact the fitting error.

Scanning techniques accuracy

Differences between the STAR-fitted meshes from the laser scan and those from the LiDAR, ZOZOSUIT2 or ZOZO_v3 in the standard zero-pose were assessed. The average RMSE between the laser scan fitted STAR mesh and the LiDAR fitted STAR mesh was 11.33 ± 4.39 mm. The average RMSE between the laser scan fitted STAR mesh and each Zozo post-processing was 7.13 ± 1.65 mm for the ZOZOSUIT2 scan, and 6.61 ± 1.93 mm for the

ZOZO_v3 (Figure 4). There was a statistical difference between the three low-cost methods, $\chi^2 = 19.79$, $p < 0.0001$. A significant difference in RMSE values was observed between LiDAR and ZOZOSUIT2 ($p = 0.0001$), as well as between LiDAR and ZOZO_v3 ($p < 0.0001$). In contrast, no significant differences were found between ZOZOSUIT2 and ZOZO_v3 ($p = 0.47$). The maximum RMSE values recorded were 20.00 mm for LiDAR, 11.43 mm for ZOZOSUIT2, and 12.63 mm for ZOZO_v3 compared to the laser scan.

The LiDAR scan showed errors across the body shape, causing participants to appear shrunken (Figures 5A and 5D). In contrast, the ZOZOSUIT2 and ZOZO_v3 primary source of error was in height estimation (Figures 5E and 5F). However, the three methods exhibited errors in the extremities, particularly around the feet and head.

The volume comparison showed a difference of $20.16 \pm 10.33\%$ for the LiDAR scan, $6.22 \pm 2.52\%$ for the ZOZOSUIT2, and $6.99 \pm 3.43\%$ for the ZOZO_v3. A significant difference was found between the three low-cost methods ($\chi^2 = 31.5$, $p < 0.0001$). LiDAR showed higher volume error than both ZOZOSUIT2 and ZOZO_v3 ($p < 0.0001$), while no difference was observed between the two ZOZO methods ($p = 1$). Laser scans generally produced higher volumes except for two LiDAR participants. The same trend was seen across body segments: LiDAR consistently showed a greater volume error than ZOZO-based methods ($p < 0.0001$), with no difference between ZOZOSUIT2 and ZOZO_v3 (Figure 6).

The absolute height differences from manual measurements were 13.84 ± 8.93 mm for laser, 20.35 ± 14.57 mm for LiDAR, 32.83 ± 14.65 mm for ZOZOSUIT2, and 22.08 ± 9.92 mm for ZOZO_v3. Laser scan was mostly overestimating participant's height while the three other methods generally underestimated the participant's height.

Anthropometric factors did not impact the scanning technique accuracy.

Effect of sex on mesh fitting and scanner errors

No sex differences were found in the fitting error for either scanning device (Figure 7). Similar findings were observed when comparing sexes in the NHH and NHHF conditions.

In the STAR-fitted standard zero-pose comparison for the LiDAR scan, female participants had a higher average RMSE (13.00 ± 3.46 mm) than male participants (10.15 ± 4.58 mm) ($p = 0.16$). The RMSE values ranged from 6.69 to 17.81 mm for females and 3.77 to 20.00 mm for males, with no notable outliers (Figure 8).

For the ZOZOSUIT2 scan, female participants had a lower average RMSE (6.31 ± 1.16 mm) compared to the males (RMSE of 7.81 ± 1.68 mm) ($p = 0.01$). These RMSE values ranged from 5.02 to 9.15 mm for females and 5.68 to 11.43 mm for males (Figure 8).

For the ZOZO_v3 condition, the average RMSE was similar between both sexes, with 6.68 ± 2.30 mm for females and 6.56 ± 1.56 mm ($p = 0.95$) for males. The RMSE values ranged from 3.47 to 12.63 mm for females and 4.25 to 18.16 mm for males.

Discussion

This study aimed to evaluate the accuracy of the LiDAR sensor with the Scaniverse app, ZOZOSUIT2 and ZOZO_v3 in capturing full body morphology in adults compared to a ground truth laser-based whole body scan. Each resulting point cloud was fitted to the STAR model [23] to facilitate scan-to-scan comparison, allowing for consistent positioning and alignment of the meshes.

The first objective was to understand the impact of STAR model fitting on raw point clouds and meshes. The fitting error for the laser scan yielded a mean average error (MAE) of 4.81 ± 0.48 , which was higher than the 3 mm reported by the STAR development team²³. This discrepancy may be due by differences in scanning hardware, environmental factors such as ambient room light²⁶ and skin reflectivity, or variation in post-processing and outlier filtering. LiDAR scans showed even greater fitting errors, likely due to common issues such as gaps or

missing regions in the point cloud data. Nevertheless, the STAR model provides a key advantage by filling these gaps and reconstructing challenging areas like the hands, head, and feet. Due to body shape or positioning, the laser scan struggled with fine details for some participants, such as hands and feet, or blending between the thighs. Additionally, features like long hair under a swim cap or a facial beard can cause deviations from the STAR model's assumptions of a 'spherical' bald head. These extremity issues can be shown by the fitting error decreasing by 5.41% for the laser scan and 9.48% for lidar after removing the hands, head, and feet. Analysis of potential sex differences in the STAR model fitting accuracy reveals similar RMSE and standard deviation between females and males for the laser and LiDAR scans. These findings suggest that shape differences do not influence the fitting accuracy. Furthermore, the STAR model includes separate population-based models for males and females, which appear to work effectively in the present study. Overall, the STAR model fitted well when focusing on the general body shape rather than the anatomical extremities. While its reduced accuracy at the fingers, toes, and head represents a topological trade-off, its ability to standardise the poses enables direct comparisons across different scan technologies. Furthermore, these limitations are outweighed by its capacity to smooth sparse LiDAR data and fill in missing regions improved its suitability for further analysis.

The second objective was to compare the LiDAR, ZOZOSUIT2 and ZOZO_v3 methodologies against the ground truth laser scan in a STAR-fitted standard zero-pose to facilitate direct comparison. Overall, the LiDAR system underperformed compared to both ZOZOSUIT2 and ZOZO_v3, except for height with similar or better result. This underperformance is underscored by mesh comparison data, with LiDAR yielding higher RMSE (11.33 ± 4.39 mm) than either ZOZOSUIT2 (7.13 ± 1.65 mm) or the ZOZO_v3 (6.61 ± 1.93 mm). Compared to ZOZOSUIT2 and ZOZO_v3, LiDAR exhibited a 37-42% higher mean RMSE and nearly twice the standard deviation. Consequently, this led to a LiDAR

exhibiting an average volume error of around 20% across full-body and segmented regions, whereas ZOZOSUIT2 and ZOZO_v3 remained under 10%. The shrunken appearance of the LiDAR scans can likely be attributed to two factors: post-processing smoothing applied by the software prior to export, and the deep skin penetration of near-infrared light²⁷, which can lead to uniform reduction in the participant's apparent volume. For the height estimation, LiDAR and ZOZO_v3 showed similar results with errors of 20 – 22 mm, while ZOZOSUIT2 displayed larger errors in average of 33 mm. In comparison, the laser scan had only an average of 13.84 mm error. The height difference in the ZOZOSUIT2 condition is likely due to the suit not covering the head and feet, which can complicate accurate height reconstruction. These findings align with previous studies reporting 10-20 mm errors between manual and laser scan measurements^{3,28}. CloudCompare heatmaps (Figure 5) confirmed that LiDAR errors were distributed across the body, resulting in participants appearing thinner. For ZOZOSUIT2 and ZOZO_v3, errors were concentrated at the head and feet, contributing to an underestimated height. Overall, ZOZO_v3 condition performed slightly better than the ZOZOSUIT2, showing lower RMSE and height error. The higher accuracy of ZOZO_v3 may be attributed to the fact that participants were wearing the suit during the scanning. Although the algorithm is designed to reconstruct the body using standard image alone, the feature present on the suit provided more consistent reference points across images than normal clothing would allow. LiDAR performed worst in the mesh comparison, with RMSE higher than the previous study, which ranged from 1 ± 1 mm to 9 ± 13 mm, depending on the scanned object¹³. However, these studies focused on small, static items, such as a violin or a fountain, which simplify the scanning process; even minimal movement can significantly affect accuracy. Furthermore, the use of different applications across studies may introduce variations in results, depending on the processing algorithm^{13,29}. A similar observation applies to the ZOZOSUIT2, which showed

an error of 3.83 mm when scanning a mannequin. Yet again, this was based on a single measurement of a static object.

An examination of the influence of sex on the performance of the three scanning techniques indicated that ZOZOSUIT2 was the only one affected by the participant's sex. Although males exhibited a wider range of errors than females for LiDAR, this discrepancy may be attributed to the larger number of male participants in the study. Even though ZOZOSUIT2 showed slightly higher error for males, the value remained close to those of the ZOZO_v3. The differences between sexes were limited, supporting the effective use of these scanning devices for both males and females.

Practical usability must also be considered. While LiDAR sensors are predominantly restricted to premium Apple devices (iPad Pro and iPhone Pro), photogrammetry-based solutions like the ZOZOSUIT2 and ZOZO_v3 can be performed on any device equipped with a standard camera. However, stereophotogrammetry often requires manual scaling using an object of known dimensions, whereas LiDAR natively captures data at the correct metric scale.

This study has several limitations. First, as only one scan of the same participants was recorded with the LiDAR and ZOZOSUIT, no test-retest reliability of either device was performed. Secondly only one application was tested with the LiDAR camera. Different applications use distinct algorithms to generate point clouds, which may have influenced the results. Scaniverse was selected because it is freely available and has shown promising results in previous work for scanning large objects ¹³. In contrast, most LiDAR applications are designed for scanning rooms or spaces. Consequently, the findings cannot be generalised to all LiDAR-based applications ^{13,30}. The scanning time between laser scan (~15s) and ZOZOSUIT2, ZOZO_v3 or LiDAR (~1-2min) can introduce postural sway and respiratory artifact impacting the fitting error and the scan comparison. Finally, the ZOZO_v3 mesh reconstruction was performed using images of participants wearing the ZOZOSUIT2, which

may have influenced the results, as the fiducial markers could have aided reconstruction compared to photos taken in tight-fitting clothing, as in the laser scan and LiDAR conditions. The pictures have not been taken without the suit as at the time of the data collection the no suit reconstruction function was not available. Additionally, the ZOZO App output underwent a dual-fitting pipeline: first through the app's with an SMPL fit, and subsequently through the STAR model to achieve a standard zero-pose. This dual-fitting pipeline might have introduce cumulative fitting errors that may have impacted the final reconstruction accuracy.

This study suggests that low-cost scanning technologies, such as LiDAR sensors, the ZOZOSUIT2, and the ZOZO_v3, can provide reasonably accurate 3D body surface geometry in an adult population. ZOZOSUIT2 and ZOZO_v3 outperformed LiDAR in mesh error and regional body volume estimation. No bias was observed in reconstructing female versus male body shapes across the three methods. The choice of technology should consider factors like ease of use and required accuracy, depending on the intended application.

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Declaration of interest statement

ZOZO Inc. and ZOZO New Zealand Limited had no role in the study's design; in the collection or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Disclosure statement

No potential competing interest was reported by the author(s).

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Author contributions

Conceptualisation: TB, KS, HW, JC; Data curation: CW, KS, HW; Formal analysis: EA, CW; Funding acquisition: TB, JC; Investigation: CW, KS, HW; Methodology: EA, KS, HW; Project administration: TB, JC; Resources: TB; Software: EA, CW; Supervision: TB, JC; Validation: EA, JC; Visualisation: EA, CW; Writing – original draft: EA; Writing – review & editing: EA, CW, TB, KS, HW, JC.

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Figure captions

Figure 1. STAR-fitted mesh pipeline across various raw data: laser scan (left), LiDAR (middle), and the ZOZO App (right).

Figure 2. Representation of the different body segments used for volume comparison (Grey parts were excluded from the body segment comparison).

Figure 3. Fitting RMSE between the laser scan (dot box) and the STAR-fitted mesh and between the LiDAR point cloud (filled box) and the STAR-fitted mesh in the three conditions: 1) full body (FB), 2) after removing the head and hands from the fitting calculation (NHH) and 3) after removing the head, hands and feet from the fitting calculation (NHHF)

Figure 4. RMSE between STAR-fitted meshes in the zero pose for: LiDAR vs. laser scan, ZOZOSUIT2 vs. laser scan, and ZOZO_v3 vs. laser scan.

Figure 5. Example of differences for a single participant. The participant was picked around the average values. A) LiDAR vs. Laser comparison CloudCompare (RMSE:13.19 mm); B) ZOZOSUIT2 vs. Laser comparison CloudCompare (RMSE: 7.63 mm); C) ZOZO_v3 vs. Laser comparison CloudCompare (RMSE: 6.28 mm); D) Visual comparison between the laser scan (red dots) and the LiDAR scan (grey mesh); E) Visual comparison between the laser scan (red dots) and the ZOZOSUIT2 scan (grey mesh); F) Visual comparison between the laser scan (red dots) and the ZOZO_v3 scan (grey mesh).

Figure 6. Volume comparisons were made between the laser scan and three other methods: LiDAR, ZOZOSUIT2, and ZOZO_v3, across six isolated body segments: right arm, left arm, upper torso, lower torso, right leg, and left leg.

Figure 7. Fitting RMSE between the laser scan and the STAR-fitted mesh and between the LiDAR point cloud and the STAR-fitted mesh for male and female in the full body (FB) condition.

524 Figure 8. RMSE comparison between STAR-fitted meshes in the zero pose for three conditions,
525 separated by sex: LiDAR vs. laser scan, ZOZOSUIT2 vs. laser scan, and ZOZO_v3 vs. laser
526 scan.

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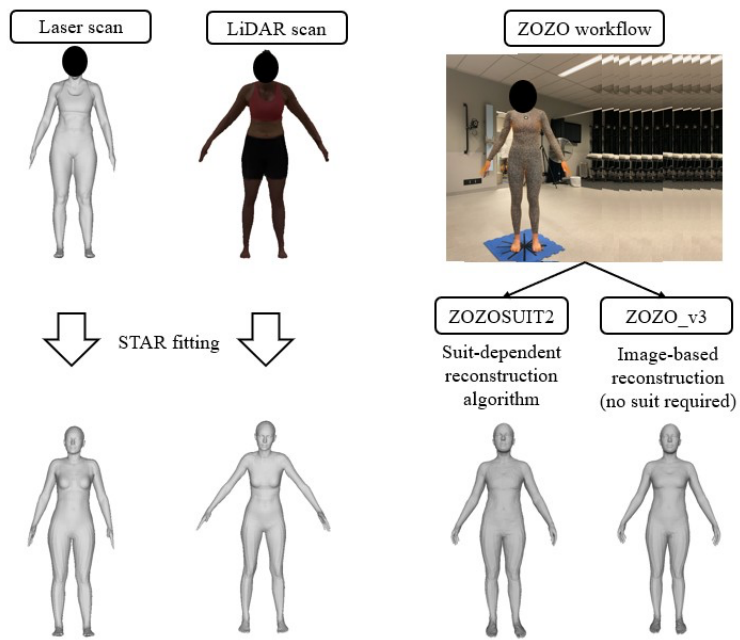
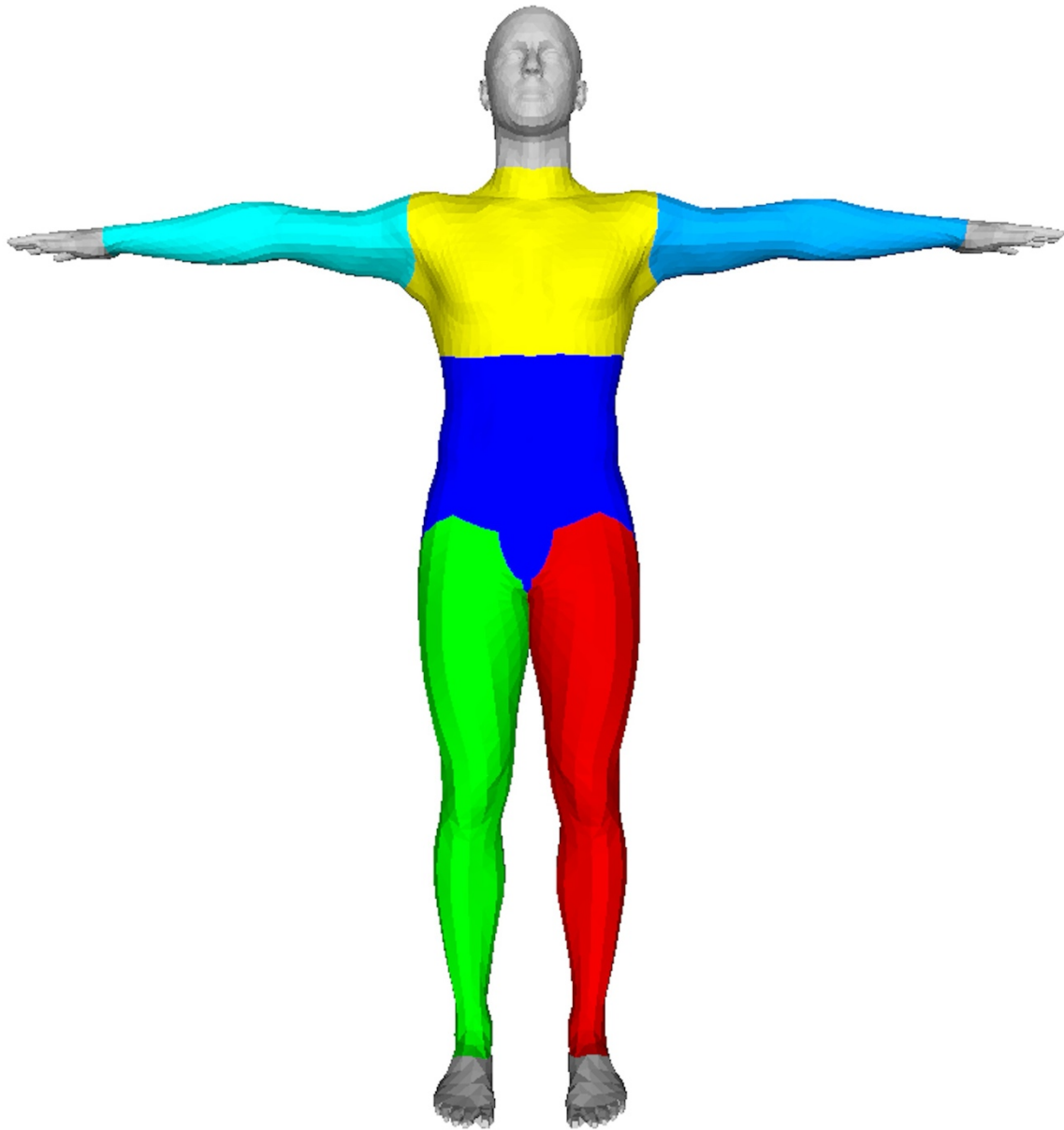


Figure 1



531

532 Figure 2

533

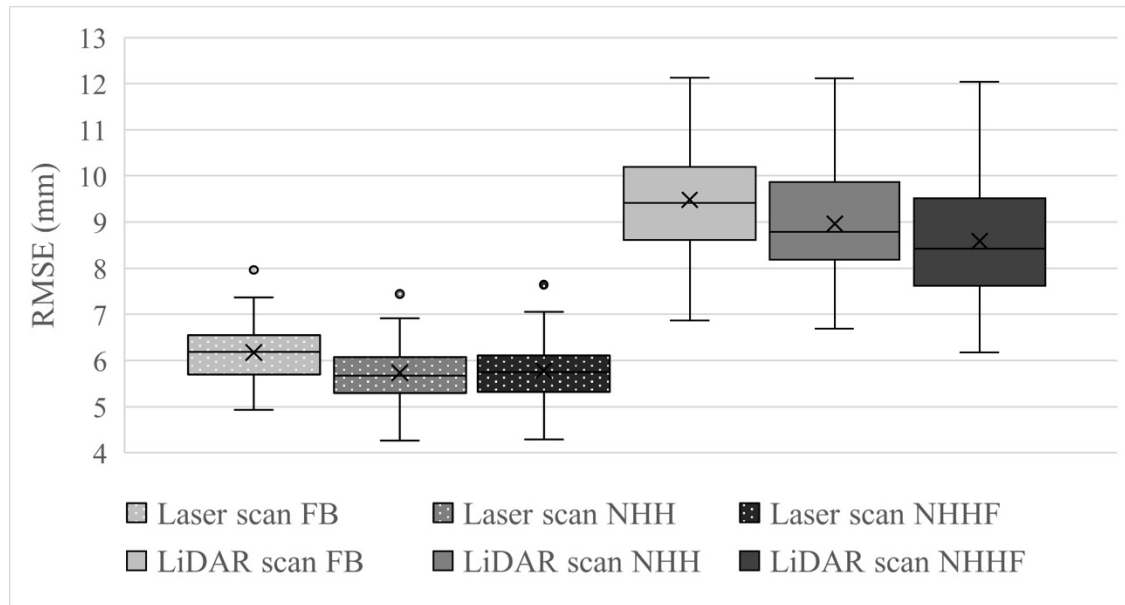


Figure 3

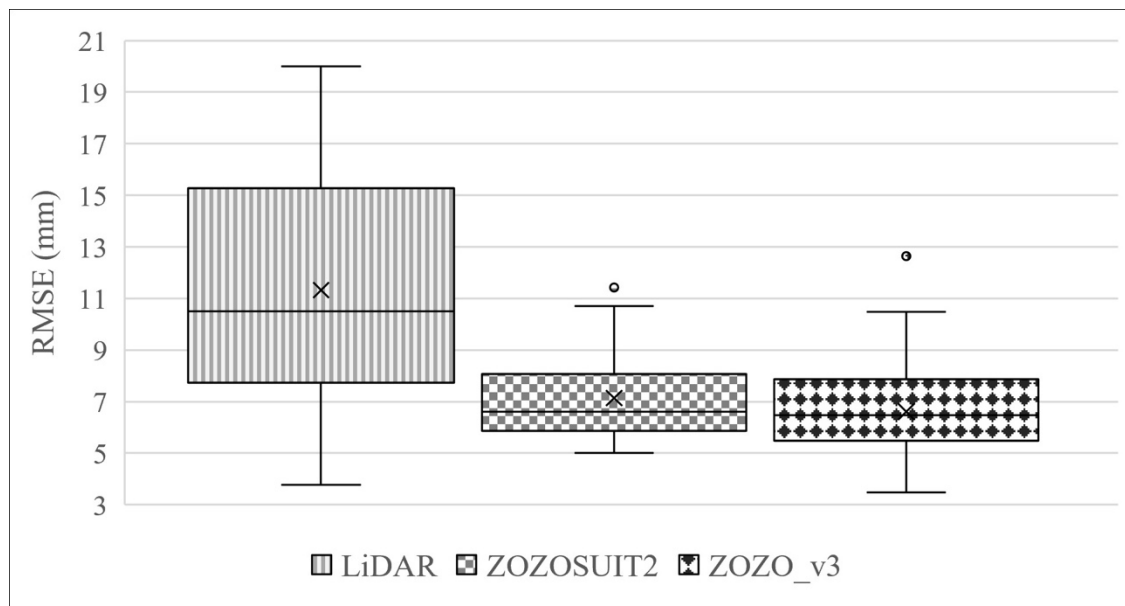


Figure 4

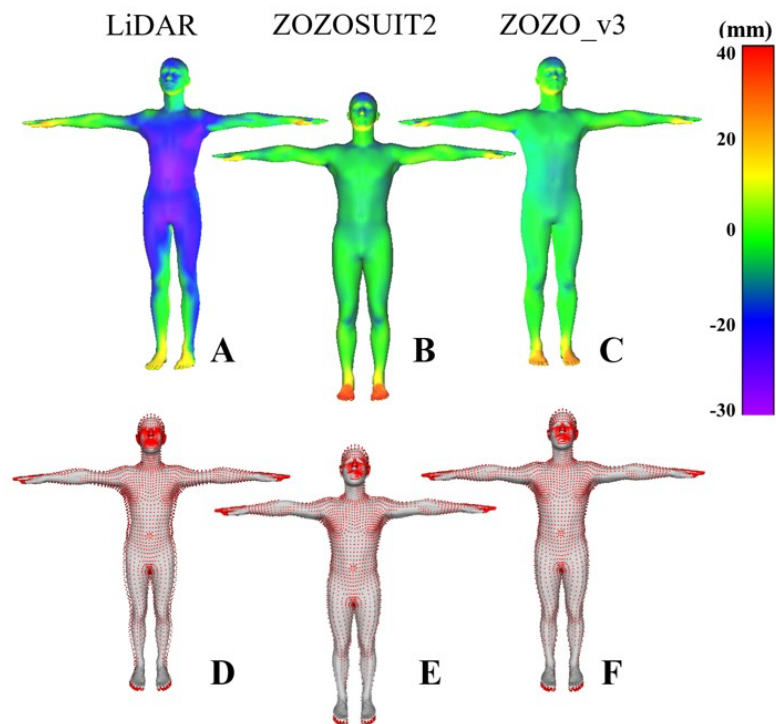


Figure 5

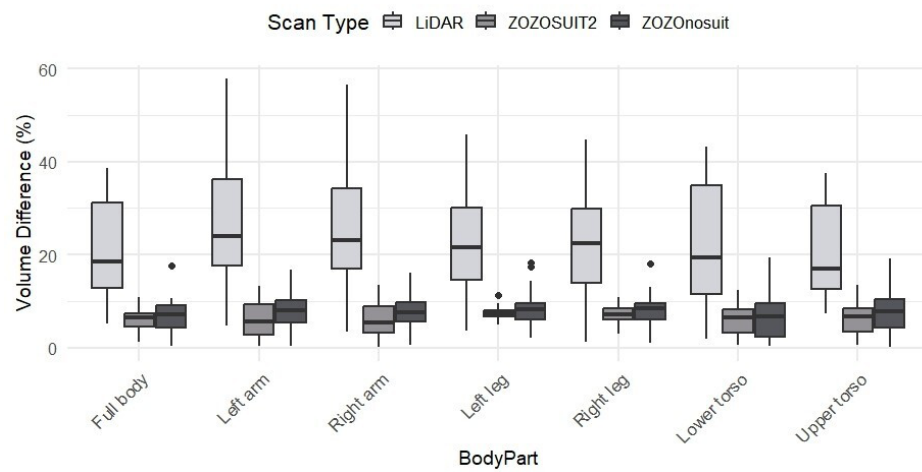


Figure 6

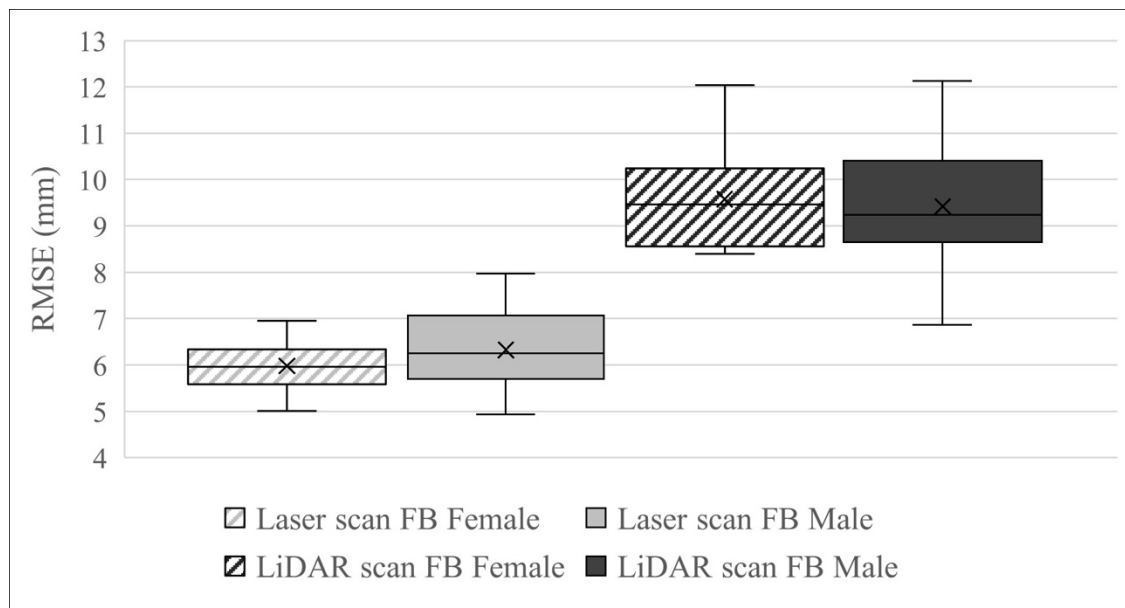


Figure 7

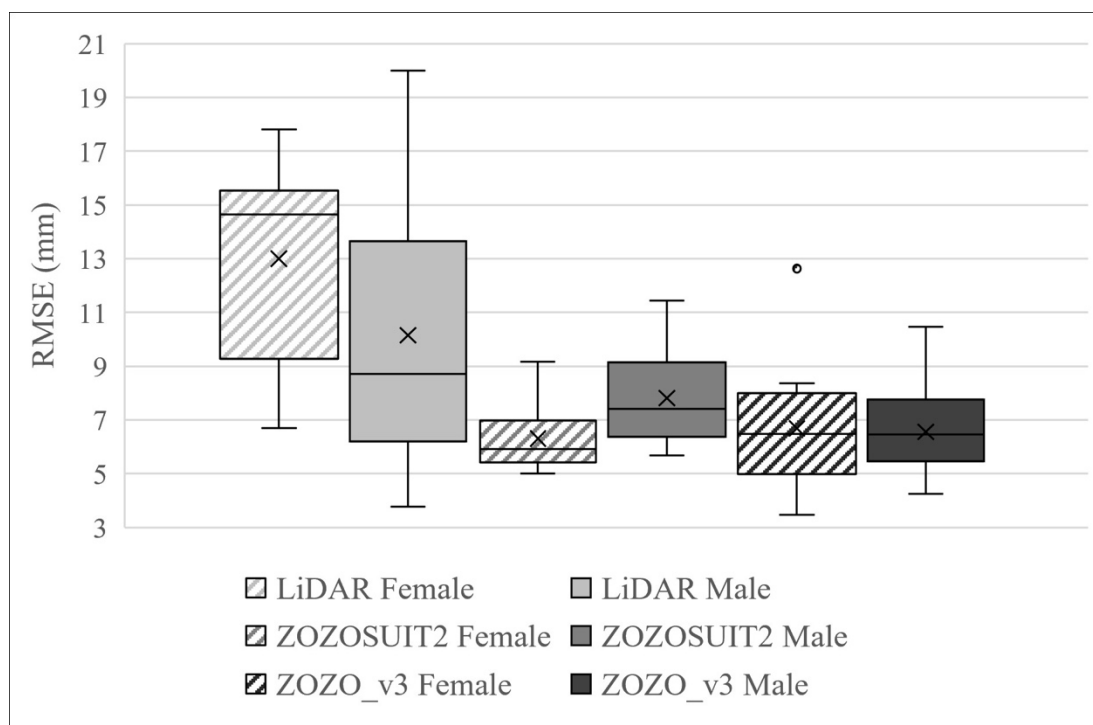


Figure 8