Improved Convex Hull Algorithm Applied to Body Size Measurements

Fang Qi¹, Sun GuangWu¹,²,³ and Chen Yu¹

¹ School of Textiles and Fashion, Shanghai University of Engineering Sciences, Shanghai 201600, China
² Textile Industrial Key Lab of Ergonomics and Functional Clothing, Shanghai University of Engineering Science, Shanghai, 201620, P.R. China
³ Sino-British Joint Lab For Smart Sportswear, Shanghai University of Engineering Science, P.R. China

Abstract. The Quickhull algorithm is a very efficient convex hull algorithm for many engineering application. Although it can be applied in the clothing industry, its conventional formulation requires massive computational resources when processing point clouds from concave parts of the human body. Thus, we improve the Quickhull algorithm and apply it to accurately estimate human body dimensions. Assuming body symmetry with respect to the sagittal plane, some concave points can be quickly deleted to reduce the number of recursions, enhancing the overall calculation efficiency. Compared with the traditional Quickhull algorithm, the efficiency of the improved algorithm increases by 15.1–24.4%. Additionally, the computation time of the improved Quickhull algorithm is about three-quarters that of Graham’s scan. We expect that this study provides insights on the application of body size measurement and estimation based on 3D scan data.

1. Introduction
Determining the human body size and dimensions is the basis for apparel design and personalization in the clothing industry. The precision of body size estimation determines the fitting, comfort, and appearance when wearing garments[1–3]. Currently, 3D scanning enables non-contact measurements with accuracy and efficiency, and thus it is widely employed in many fields[4–7]. For body dimensions, measurements using a 3D scanner provide point clouds of the body. Then, a convex hull algorithm can be applied to calculate the corresponding dimensions[8]. The convex hull algorithm is widely applied to process images, and various methods have been proposed to improve this algorithm, such as the bisection method[9], method of orienting curves[10], Graham’s scan[11], and Quickhull algorithm[12].

Graham’s scan is a simple method to entirely and stably process point clouds acquired from the body of a subject. Therefore, Graham’s scan is extensively used in clothing industry. For instance, Ge et al.[13] used Graham’s scan in a 3D scanning system to calculate the circumference of the convex hull of plane clouds. They obtained a small error range with respect to manual measurements, verifying the reliability and stability of Graham’s scan. Lai et al.[14] used Graham’s scan to obtain the convex hull for accurate estimation of the body circumference. However, the number of backtracking verifications in Graham’s scan increases rapidly when many concave points exist in the point clouds. In fact, it is possible to backtrack nearly 50% of the points in a point cloud for the regression of only one point. To
solve this problem, Li et al.\cite{15} removed concave points before calculating the convex hull. However, this method failed to reduce the computation time, despite improving the calculation efficiency.

Unlike Graham’s scan, the Quickhull algorithm can remove noise and useless points before computing the convex hull from a point cloud. Additionally, the Quickhull algorithm is efficient and has been applied in many areas\cite{16-18}. For example, Liu et al.\cite{19} improved the Quickhull algorithm by deleting a large number of points using an initial convex sphere in a multi-dimensional space. This improved algorithm was inspired by human visual perception to reduce the number of computations. Compared with the conventional algorithm, it improves the spatial efficiency and provides a fast computing scheme for the convex hull obtained from a point cloud. Kallrath and Frey\cite{20} also improved the Quickhull algorithm by adopting a subgradient method to solve the non-smooth convex optimization problem during convex hull calculation. This improved algorithm increases the computation speed by one-third compared with the conventional Quickhull algorithm.

High precision requirements result in massive data generation from a scanned subject, and the large point clouds increase the computation time and complexity. Using the Quickhull algorithm to calculate body dimensions. To this end, we improve the original algorithm and propose the simple Quickhull algorithm (SQA) that assumes human body symmetry with respect to the sagittal plane. Compared with the traditional formulation of Graham’s scan, SQA can reduce the time complexity, reducing the computation time while maintaining the estimation accuracy of human body dimensions.

2. Method
Based on the efficient characteristics of the Quickhull algorithm, we propose the SQA that comprises three stages. In the first stage, a rectangular coordinate system is used to detect the coordinates of the extreme points. In the second stage, additional extreme points are obtained and recursively selected to determine an extended convex hull. In the third stage, the points in the convex hull are connected and its circumference is calculated. The proposed SQA is detailed below.

2.1. Extreme point coordinates
We represent point clouds from the human body acquired using three-dimensional spatial coordinates. The height direction is defined as the $Z$ axis, and the side and front of the body are defined as the $X$ and $Y$ axes, respectively. Figure 1 illustrates the symmetry of the human body with respect to the sagittal plane. Moreover, it is easy to handle key positions of the chest and hip on the transverse plane. For example, the chest cleavage and hip groin are concave shapes that should be processed to estimate the body dimensions.

By dividing the point cloud distributions into four quadrants on the transverse plane, the number of recursive calculations can be reduced, thus improving efficiency. For instance, in the chest section shown in Figure 2, as left and right breast points are extreme points along the $Y$ axis in the first and second quadrants, they can be directly connected when calculating the chest convex hull, and the points between these two extreme points can be discarded.

![Figure 1. Point clouds of human chest, waist, and hipline on the transverse plane.](image1)

![Figure 2. Point clouds of human chest section.](image2)

2.2. Convex hull points
The convex hull points of the cross-section are essential to calculate the body dimensions. They can be calculated in two main steps: 1) establish the initial convex hull and 2) expand the initial convex hull by recursive calculation.

2.2.1. Initial convex hull To establish the initial convex hull, we should divide the point cloud area and find the location of the extreme points. For example, the extreme points of the negative X axis and positive Y axis are located in quadrant 2. Figure 3 shows the extreme points along each axis. The points are denoted by their axes, and their quadrants are identified by subscripts as follows: \(X_1, Y_1, X_2, Y_2, X_3, Y_3, X_4, \) and \(Y_4\).

Although the extreme points along the \(X\) and \(Y\) axes may overlap in a quadrant, the number of extreme points has no effect on the proposed SQA, and hence this is immaterial to the algorithm. Figure 4 shows the eight extreme points from the point cloud of the chest contour on the transverse plane. The points are successively connected to obtain the initial convex hull of the chest.

![Figure 3. Region division of chest point cloud.](image1)

![Figure 4. Initial convex hull and point cloud of chest.](image2)

2.2.2. Extended convex hull To extend this convex hull, we create a new set of convex hull points \(U\), and add the initial convex hull points of the chest to \(U\). Then, we delete the points inside the initial convex hull polygon, and add the remaining points to set \(U\). Then, we use the extended set \(U\) to iteratively determine the convex hull points of the chest in the four quadrants as detailed below.

Consider the initial convex hull line segment, \(A_1A_2\), on the plane shown in Figure 5. The points above segment \(A_1A_2\) are sequentially evaluated in the anticlockwise direction. There must be a point \(a_i\) having the maximum distance to segment \(A_1A_2\). Point \(a_i\) is used to evaluate new convex hull points. Specifically, determining segments \(A_1a_i\) and \(a_iA_2\) to form a triangle with segment \(A_1A_2\), we remove the extra points on the interior and along the segments. Finally, we add point \(a_i\) to the convex hull points \(U\) and reorder the midpoints of \(U\).

![Figure 5. Recursive calculation of finding new convex hull points](image3)

This method recursively finds new convex hull points in each subregion and expands the initial convex hull until the largest convex hull of the chest is obtained. The maximum distance from a point to a line segment is used to determine whether a point belongs to the convex hull. The distance, \(d\), satisfies the following formula:

\[
d = \frac{|aX + bY + c|}{\sqrt{a^2 + b^2}}
\]

The steps to extend the convex hull are summarized as follows:

1. Determine whether the initial convex hull of the chest has collinear points. If there are collinear points in \(U\), only the points at both ends of the line segment are retained.
2. Starting from line segment $X_1Y_1$, the point-to-line distance evaluation using the current convex hull is sequentially performed in the counterclockwise direction. If there are no points above a line segment (e.g., $Y_1X_2$), skip directly.

3. Find the farthest point offline on every current convex hull line segment, and add this point as a new convex hull point in $U$, which should be reordered. Connect the convex hull points around this point to form a triangle and delete the points inside or on the triangle.

4. Repeat steps 2 and 3 until processing all the points in the point cloud.

2.3. Dimension calculations
We found the convex hull vertices recursively using the method detailed above. Figure 6 shows the obtained convex hull points from a point cloud of the chest plane. We sequentially connected the convex hull points to determine the chest circumference size. Accordingly, Figures 7 and 8 show the convex hulls to obtain waist and hipline circumferences.

3. Results and Discussion
We compared the proposed SQA with the conventional Quickhull algorithm and Graham’s scan in terms of convex hull circumference and computation time of the equivalent point clouds. All the algorithms were implemented in Microsoft Visual C++ 6.0 using the language debug mode and executed in Windows 7 running on an Intel i7 processor with 8 GB of memory.

3.1. Accuracy evaluation
We compared the SQA with the original Graham’s scan, which is an accurate method, to calculate the circumference of the convex hull of the point clouds, obtaining the results listed in Table 1.

|                      | Chest (cm) | Waist (cm) | Hipline (cm) |
|----------------------|------------|------------|--------------|
| Proposed SQA         | 112.565    | 96.082     | 112.873      |
| Graham’s scan        | 112.614    | 96.153     | 112.845      |
| Difference           | 0.049      | 0.071      | −0.028       |
The circumference differences between SQA and Graham’s scan are small, remaining below ±0.1 cm, which represents less than 0.1% difference. By calculating the circumferences of the chest, waist, and hip line, we verify that the proposed SQA can accurately extract the convex hulls and be used to determine the body dimensions.

3.2. Efficiency comparison

In Figure 9, for less than 300 samples in a point cloud, Graham’s scan shows the highest efficiency. However, for larger point clouds, the efficiency of Graham’s scan is lower than that of both the Quickhull algorithm and proposed SQA. Such large point clouds are increasingly available because the scanning accuracy continuously increases in modern devices. The calculation time of SQA is notably shorter than that of Graham’s scan. Compared with the Quickhull algorithm, SQA reduces the calculation time by 15.1–24.4%. Overall, the proposed SQA is more efficient than Graham’s scan and the conventional Quickhull algorithm while providing high accuracy.

4. Conclusion

Convex hull algorithms are commonly used to process and extract information from point clouds. Although Graham’s scan is stable and widely used in many fields, the deletion of a concave point requires the processing almost half of the points. Therefore, to estimating body dimensions from convex hulls, a more efficient algorithm should be devised. We propose the SQA that can delete concave points in point clouds from body cross-sections on the transverse plane considering body symmetry with respect to the sagittal plane. Thus, the number of samples in point clouds are reduced to improve the calculation efficiency. SQA provides similar accuracy to Graham’s scan, thus providing accurate estimations of human body dimensions. Unlike Graham’s scan, SQA can efficiently process massive point clouds. In fact, the computation time of Graham’s scan strongly increases for point clouds with more than 1000 samples. In contrast, the computation time of SQA slightly increases as the point cloud becomes larger. Compared with the conventional Quickhull algorithm, the efficiency of SQA also increases by 15.1–24.4%. As accuracy continuously increases in 3D scanning devices, massive point

| No. samples in point cloud | 149 | 282 | 423 | 564 | 705 | 846 | 987 | 1128 | 1269 |
|----------------------------|-----|-----|-----|-----|-----|-----|-----|-------|-------|
| Graham’s scan              | 538 | 744 | 1201| 1739| 2339| 3092| 3869| 4775  | 7885  |
| Quickhull algorithm        | 576 | 765 | 1176| 1583| 2068| 2639| 3353| 4126  | 5622  |
| Proposed SQA               | 488 | 651 | 974 | 1197| 1625| 2124| 2796| 3476  | 4522  |

Figure 9. Calculation time of SQA, Quickhull algorithm, and Graham’s scan according to number of samples in the point clouds
clouds are available, and the proposed SQA becomes increasingly suitable to efficiently determine the convex hull from point clouds.

Acknowledgments
This research was funded by the Program for Professor of Special Appointment (Eastern Scholar) for Shanghai Institutions of Higher Learning (Grant No. TP2017074).

References
[1] Ying, Xin; Liu, Zheng; Chen, Guang; Zou, Fengyuan. The impact of body surface convex angle on dressed waist ease, International Journal of Clothing Science and Technology, 2019, 40(10):152–157.
[2] Xu, Jihong; Zhang, Wenbin; Xiao, Ping. Factors influencing the area porosity between human body and garment characteristic surface, Journal of Tianjin University of Technology, 2009, 28(01):27–32.
[3] Lage, Agne; Ancutiene. Kristina. Virtual try-on technologies in the clothing industry. Part 1: investigation of distance ease between body and garment, The Journal of the Textile Institute, 2017, 108(10):1787–1793.
[4] Kim, Dong Eun. Analysis of body shape and anthropometric measurements of US middle-aged women using 3D body scan data, The Research Journal of the Costume Culture, 2015, 23(04):726–736.
[5] Kuehnapfe, Andreas; Ahnert, Peter; Loeffler, Markus; Scholz, Markus. Body surface assessment with 3D laser-based anthropometry: Reliability, validation, and improvement of empirical surface formulae, European Journal of Applied Physiology, 2017, 117(2):371–380.
[6] Bezerra, G.; Carvalho, M.; Araujo, A.; Roeha, M.; Barboza, R. Analysis of body differences for the design of children’s clothing, Materials Science and Engineering, 2018, 459(1):012073.
[7] Yan, Song; Wirta, Johan; Kämäräinen, Joni-Kristian. Anthropometric clothing measurements from 3D body scans, Machine Vision and Applications, 2020, 31(1):1.
[8] Park, Se Jin; Min, Seung Nam; Lee, Heeran; Subramaniyam, Murali; Ahn, Sang Jae. 3D hand anthropometry of Korean teenagers and comparison with manual method, International Conference on Human-Computer Interaction, 2014, 491–495.
[9] Linh, Nguyen Kieu; Muu, Le Dung. A convex hull algorithm for solving a location problem, RAIRO Operations Research, 2015, 49(3):589–600.
[10] Thanh An, Phan. Method of orienting curves for determining the convex hull of a finite set of points in the plane, Optimization, 2010, 59(2):175–179.
[11] Singh, Navjot; Arya, Rinki; Agrawal, R.K. A convex hull approach in conjunction with Gaussian mixture model for salient object detection, Digital Signal Processing, 2016, 55:22–31.
[12] Graham, Ronald L. An efficient algorithm for determining the convex hull of a finite planar set, Information Processing Letters, 1972, 1(4):132–133.
[13] Ge, Baozhen; Guo, Huating; Peng, Bo et al. Automatic model style measurement based on automatic body feature extraction from 3-D scanning data, Journal of Textile Research, 2012, 33(4):129–135.
[14] Lai, Jun; Wang, Bo; Fu, Quan. Automatic extraction method of human body sizes based on 3D point clouds, Journal of Central South University (Science and Technology Edition), 2014, 45(8):2676–2683.
[15] Li, Xiaozhi; Li, Xiaojiu; Liu, Hao. Calculation of girth size based on point cloud of human body section, Journal of Textile Research, 2019, 40(7):128–132.
[16] Liu, Kai; Xia, Miao; Yang, Xiaomei. An effective 2D convex hull algorithm, Advanced Engineering Sciences, 2017, 49(5):109–116.
[17] Nguyen, Kieu Linh; Song, Chanyoung; Ryu, Joonghyun; Thanh An, Phan; Hoang, Nam-Dung; Kim, Deok-Soo. QuickhullDisk: A faster convex hull algorithm for disks, Applied Mathematics and Computation, 2019, 363:124626.
[18] Li, Bidong; Yan, Haowen; Wang, Zhonghui et al. Algorithm of convex hull generation for point sets based on sorted coordinate, Science of Surveying and Mapping, 2017, 42(2):14–17.
[19] Liu, Runzong; Tang, Yuan Yan; Chan, Patrick PK. A fast convex hull algorithm inspired by human visual perception, Multimedia Tools and Applications, 2018, 77(23):31221–31237.
[20] Kallrath, Josef; Frey, Markus M. Packing circles into perimeter-minimizing convex hulls, Journal of Global Optimization, 2019, 73(4):723–759.