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Turin Shroud: Compatibility Between a Digitized Body Image and a Computerized Anthropomorphous Manikin

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Abstract. *The front image of the Turin Shroud, 1.95 m long, is not directly compatible with the back image, 2.02 m long. In order to verify the possibility that both images were generated by the same human body, a numeric-anthropomorphous manikin was constructed by computer and wrapped in the digitized front and back images. The manikin was made to move, within the limits allowed by normal limb movements, with the aim of finding correspondences between predefined anthropometric points on the Shroud and on the manikin itself. Kinematic analysis showed the most probable position of the arms, which are not completely visible on the Shroud, due to damage during the fire of 1532. A part from the hands afterward placed on the pubic area, the front and back images are compatible with the Shroud being used to wrap the body of a man 175±2* cm *tall, which, due to cadaveric rigidity, remained in the same position it would have assumed during crucifixion. The position of this Man was assessed in terms of the angles of the legs and arms and the forward tilt of the head. © 2010 Society for Imaging Science and Technology.*
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INTRODUCTION

The Turin Shroud (TS) is a 4.4 m-long and 1.1 m-wide linen cloth believed to have enveloped the corpse of a scourged, thorn-crowned man who was crucified and stabbed in the side with a lance.[1–3] There are also many marks caused by blood, fire, water, and folding apparent on the cloth that partially obscure the indelible double body image (front and back). The wounds are what interest forensic pathologists most because they would be difficult to produce. The body image is extremely superficial, but in some areas of the frontal image, such as those of the face and perhaps the hands, it is superficial on both sides.[4]

The TS is believed by many to be the burial cloth which Jesus Christ was enveloped in when placed in a tomb in Palestine about 2000 years ago. It is the most important relic of Christianity and has generated more controversy than any other relic.

Scientific interest in the TS started in 1898 when Pia, who photographed it, noticed that the negative image on the TS looked like a photographic positive. The luminance levels of the body image can be related to the three-dimensional (3D) image of a human body.[5,6]

The most important scientific analysis of the TS performed in 1978 by STURP (Shroud of TUrin Research Project)[2,3,7] found no explanations for the body image impressed on it. The characteristics of the TS body image are very unique and impossible for now to be reproduced all together[8,9] even if many different hypotheses, frequently supported by experimental results, have been stated.[10,11] Although good experimental results have been obtained, these proposals are unable to describe all of the characteristics of the body image listed.[9]

Some examples of proposed hypotheses are listed below.

(1) The image, which originated from the direct contact of a body with the cloth, is due to a natural chemical reaction, perhaps similar to the effect of herbaria leaves.[12]
(2) The image was the result of the emanation of ammonia vapor[13,14] or the interaction of gases produced by the corpse with substances derived from retting of the linen.[12]
(3) The image is a painting: many techniques have been proposed, but the best results have been obtained using a modified carbon dust drawing technique.[15]
(4) It was obtained from a warmed bas-relief.[5,16]
(5) It was obtained by rubbing a bas-relief with pigments or acids.[17]
(6) It was obtained by exposing linen in a darkened room using chemical agents available in the Middle Ages.[18]

Although good experimental results have been obtained on the basis of hypotheses No. 1–6, these proposals are unable to describe all of the characteristics of the body image.[9]

The hypothesis of a source of radiation has a large consensus even if some points must be still be demonstrated. The source of energy may be due to a corona discharge although, due to the need to manage relatively high sources of directional energy, no complete experiments have been done.[1]

The TS body image is composed of a front image of 1.95 m long and a back image of 2.02 m long, separated from the former by a nonimage zone of 0.18 m[19,20] (data from measurements done before 2002). Some doubts remain regarding the characteristics of the Man who was wrapped in the TS. First, some distortion[21] in the front body image are

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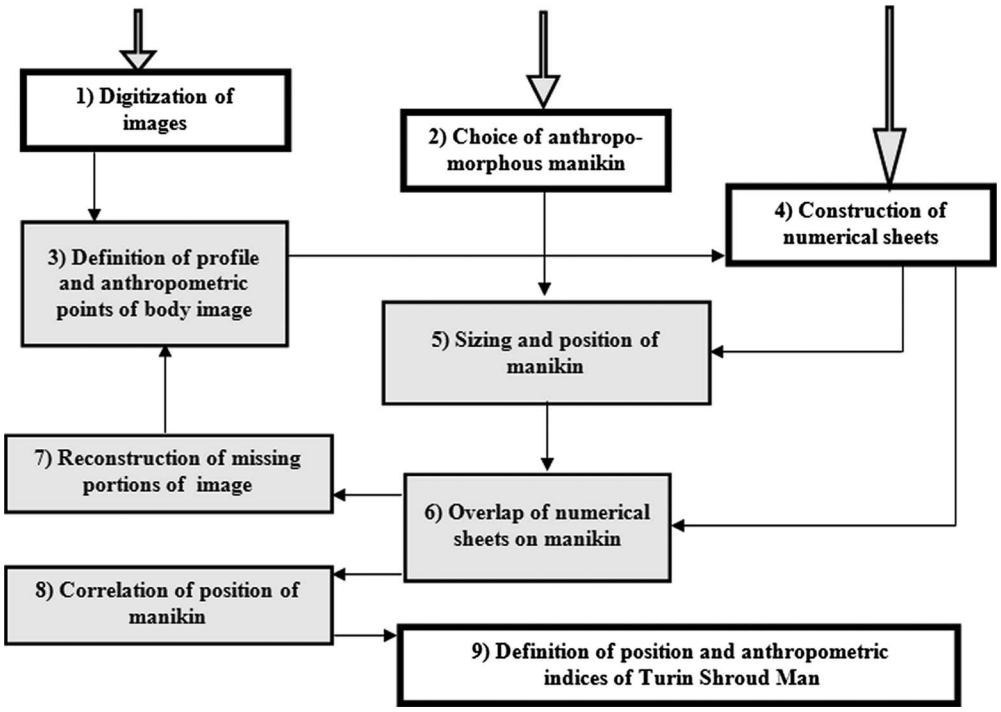

Figure 1. Diagram of method used to verify compatibility between digitized body image and anthropomorphous manikin.

evident, e.g., points corresponding to the hands and calves, which exclude any kind of direct photographic procedure[18] used to obtain the image.

The type of image is not even directly consistent with the Shroud being wrapped around the body, as is the case of the bloodstains,[22–24] which formed before the body image.[1] In addition, the two images are clearly not directly dimensionally compatible with each other, and their length would indicate a perhaps excessively tall man. However, as will be shown, the TS Man (TSM) was not in a supine position but, according to the *rigor mortis* which began after his crucifixion, had his head tilted forward, his knees slightly bent, and his feet extended as a result of nailing.

The aim of this work is to size a numerical manikin and see if it is possible to find a position compatible with both front and back images of the TSM; finally an experimental verification is done to confirm the results.

ANALYSIS METHOD

Figure 1 summarizes the procedure used to verify compatibility between front and back body images.

First (step 1), photographs of the front and back images of the TSM were digitized, using the photographs taken in 1931 by Enrie with orthocromatic film (by kind permission of the Scoffone di A. Guerreschi photographic studio).

Step 2 was to choose an anthropomorphous manikin, which could be moved by computer according to all the possible kinematics of a human body. This model was composed using Poser software, choosing a body of longilinear, muscular type.

The size of the manikin could be changed according to the anthropometric parameters measured on the TS. Front and back images were analyzed by vision systems in order to define their profiles and the corresponding anthropometric points (henceforth a-points) (step 3) to be used for the numerical sheets and the manikin.

In particular, the profiles of the front and back body images were determined by analyzing the luminance (or gray) levels of the digitized images and, from these, the relative a-points. Some of these, e.g., those of the shoulders and arms, which are not visible on the body image of the TS, were reconstructed by an iterative procedure based on overlapping sheets on the manikin.

Then two numerical sheets were constructed, front and back, on which the previously defined a-points were positioned (step 4). Step 5 consisted of defining the size and preliminary position of the manikin (step 3) by kinematic modeling.

The size of the manikin was determined after having verified that the length of the limbs on the front body image were compatible with those of the back.

In step 6, the two sheets were overlapped on the manikin, to verify if there was a position in which compatibility of all the a-points could be verified. Once the numerical manikin had been constructed, kinematic analysis was carried out to determine the most probable position of the shoulders and arms, according to the known position of the hands and forearms. In step 7, the sheets placed on the manikin reproduced the missing parts of the body image of the TSM.

According to the congruence between the a-points of the sheets and the manikin (step 8), the latter was improved both from the dimensional viewpoint by defining the sizes of

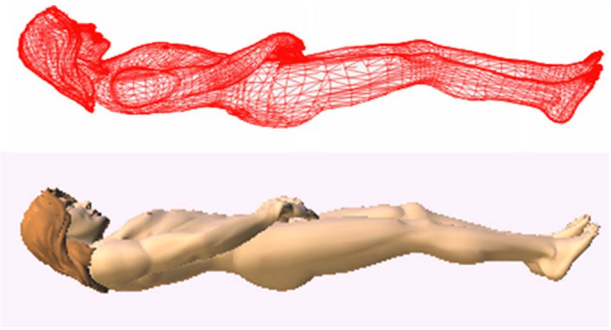

Figure 2. Two versions of manikin resulting from definition of position and anthropometric indices following analysis described in Fig. 1.

the limbs, and from that of its position, defining the angles of head, knees, and feet.

Limb angles were determined according to the lengthening or shortening of the front and back sheets by hypothesizing the absence of folds in the Shroud which would be probable if the body had simply been rested on one sheet and if, later, that same sheet had been turned back on itself to cover the upper part of the body without completely wrapping its sides.

Although some authors have hypothesized folds in the Shroud[25] and ropes around the body of the TSM, it is believed that the body image is that of a sheet simply laid out on a body, because there are no evident interruptions in body image or bloodstains. This hypothesis derives from some general observations regarding the body image, which would make complete wrapping, including the sides, less probable: in this case, even in bearing in mind the possibility of radiation normal to the emitting surface,[1,26] the authors believe the side area of the body which is impressed on the Shroud should be larger.

Once the manikin had been constructed, compatible with wrapping of both front and back images, the probable size and position of the TSM were defined (step 9) (Figure 2).

DEFINITION OF BODY IMAGE PROFILE AND A-POINTS

Defining the body image profile of the TSM, obtained by successive approximations, required reconstruction of those parts of the image damaged by the Chambéry fire of 1532.

The digitized front image of the TS is shown in Figure 3 and the corresponding positions with respect to origins of axes x and y in Table I. The back image is shown in Figure 4 and the corresponding points in Table II.

The a-points were defined not referring to the dimensions of the TS, i.e., 436 cm long and 112 cm wide, but to those of the digitized image shown in the figures. Uncertainty of measurement is ± 0.05 cm.

Defining the reference points required determination of the a-points, in the hypothesis of double correspondence between anatomical and skeletal anatomy.

Skeletal points are preferred to superficial ones, because they are internal, can be identified by tactile search, and are

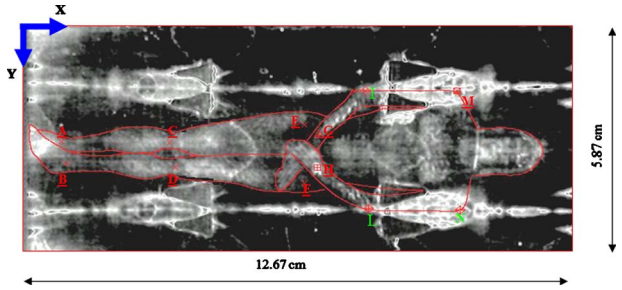

Figure 3. Reference a-points on front image, determined before checking of compatibility with manikin.

Table I. Coordinates of a-points in reference system of front image of Fig. 3.

	X (cm)	Y (cm)
A	0.8	3.0
B	0.6	3.5
C	3.25	3.0
D	3.4	3.7
E	6.3	2.5
F	6.3	4.0
G	6.65	2.9
H	6.6	3.65
I	7.7	1.7
L	7.8	4.7
M	9.8	1.7
N	9.9	4.75

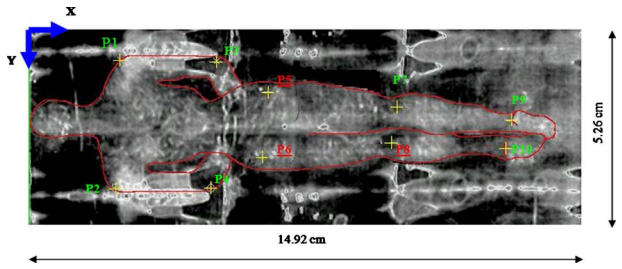

Figure 4. Reference a-points on back image, determined before checking of compatibility with manikin.

not subject to variations; superficial ones are external points identified on the skin. Skeletal points are established by marking their projection on the skin, i.e., the operator's finger, in an attempt to find the points of reference of bones, must not remain still on the skin, thereby stretching it, but must be moved about and pressed very gently downward until the point in question is reached. In the case of the image on the TS, these points of reference can obviously only be those on soft tissues, and uncertainty in definition may be about 1 cm.

Table II. Coordinates of a-points in reference system of back image of Fig. 4.

	X (cm)	Y (cm)
P1	2.42	0.95
P2	2.4	4.3
P3	5	0.9
P4	4.9	4.3
P5	6.4	1.75
P6	6.3	3.5
P7	9.9	2.15
P8	9.7	3.1
P9	13	2.5
P10	12.8	3.25

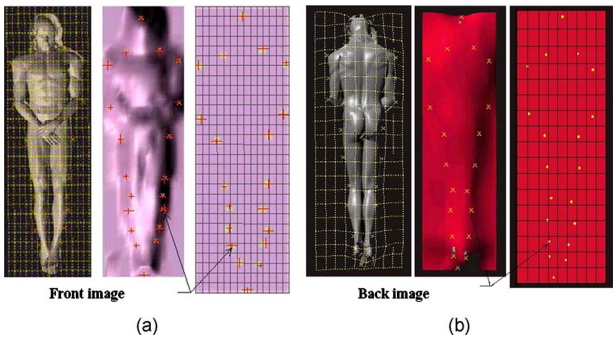

Figure 5. Numerical sheets, (a) front and (b) back, in "wrapped" position (center) and stretched out (right), with profile points of TSM belonging to them.

CONSTRUCTION OF NUMERICAL SHEETS

Two numerical sheets (henceforth n-sheets), for front and back images, were constructed. Each was composed of 1440 right-angled triangles, all equal, and later modified according to their positions on the manikin. A certain amount of plasticity of damp sheets as they were placed on the body was hypothesized. Both front and back sheets were 2.18 m long and 1.12 m wide. The coordinates of the a-points were then defined on the n-sheets. Other characteristic points of the profile of the TS image were also defined on the n-sheets (Figure 5).

CONSTRUCTION OF MANIKIN

Forensic analysis[27,28] indicates that the Man wrapped in the Shroud was in an very evident rigor mortis and it was positioned so as a crucified man taken down from the cross: head tilted forward, knees slightly bent, feet stretched out, hands afterward placed on the pubic area. Confirmation of this hypothesis comes from the shape of the gluteal muscles, which show no signs of flattening as a result of bodyweight, which would be normal if the body had not been rigid.

The manikin, constructed by means of a computer, reproduced these characteristics. Once the initial configuration

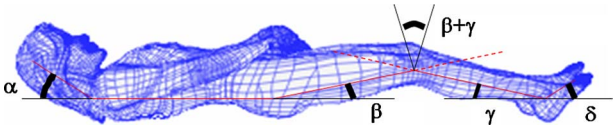

Figure 6. Angular positions varied to verify compatibility between manikin and front and back body images of TS.

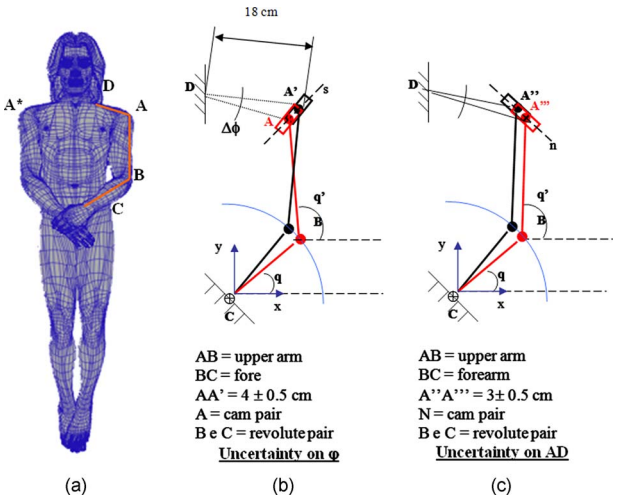

Figure 7. (a) Manikin and kinematic scheme of arms; (b) kinematic scheme of arms considering uncertainty in determining exact position of point A; (c) kinematic scheme of arms considering uncertainty in determining exact length of segment AD.

of the manikin had been established, the following angular parameters were chosen, to be varied following the congruence, if any, with the a-points on the n-sheets (see Figure 6):

(i) α: angle of head;
(ii) β_1 and β_2: angles of right and left femurs;
(iii) γ_1 and γ_2: angles of right and left tibias;
(iv) δ_1 and δ_2: angles of right and left feet.

KINEMATIC ANALYSIS OF ARMS

This analysis aimed at determining the position of the arms of the TSM. It exploits data from the front and back images of the TS; unknown data are the angular positions of the upper arms.

The position of the hands and length AB and CB of arms were measured on the front and back images, and were respectively 35 ± 1 and 26 ± 1 cm.

The width of the shoulders (distance between points A and A*, called acromion; Figure 7) was evaluated as follows: the width on the manikin is 51.0 ± 0.5 cm; a series of measurements on average adult males indicates that segment AD is normally $(35\%\pm2\%)$ of segment AA′; thus, $AD=18.0\pm0.5$ cm.

Angles q and q′ of the arms are given by the Cartesian positions (x_A, y_A) of point A, according to the system of kinematic equations,

Table III. Threshold values of Cartesian coordinates of point A of left shoulder, [see Figs. 7(b) and 7(c)] according to uncertainties considered.

	x_A (cm)	y_A (cm)
Point A	17.0	50.0
Point A′	18.5	54.1
Point A″	17.5	48.5
Point A‴	18.0	52.0

Table IV. Threshold values and mean of angles q and q′ for arms according to threshold positions of point A [see Fig. 7(b) and 7(c)].

	Left q (deg)	Left q′ (deg)	Right q (deg)	Right q′ (deg)
A	35±2	97±3	42±2	92±3
A′	48±2	88±3	50±2	85±3
A″	43±2	91±3	51±2	89±3
A‴	39±2	90±3	45±2	90±3
A average	41	91	47	89

$$\begin{cases} x_A = BC \cos q + AB \cos q' \\ y_A = BC \sin q + AB \sin q' \end{cases}.$$

The coordinates of point A, belonging to lines s and n [Figs. 7(b) and 7(c)] are known, but with non-negligible uncertainty: in particular, uncertainty is 4 cm along line s [Fig. 7(b)] and 3 cm along line n [Fig. 7(c)].

The possible angles are obtained by inserting the threshold values of the corresponding Cartesian coordinates of point A into the system of kinematic equations, evaluated with respect to point C. Table III shows the coordinates of the left hand and Table IV the forearm angles.

These results yield the possible threshold profiles for the front image of the TS (Figure 8). The shoulder angles turn out to be $\varphi_1 = 10 \pm 1°$ (right) and $\varphi_2 = 12 \pm 1°$ (left).

OVERLAP OF N-SHEETS AND RECONSTRUCTION OF MISSING PARTS OF BODY IMAGE

The front and back n-sheets were placed on and under the manikin, in conformity with the body image of the TS (Figure 9).

As the TS may have been impregnated with substances traditionally used for delaying putrefaction and was therefore damp, the n-sheet was examined in the following different conditions:

(A) sheet simply laid over body and almost completely stretched, with elastoplastic lowering of not more than 2 cm (front sheet) or 1 cm (back sheet) with respect to the position of a perfectly stretched sheet;
(B) sheet simply laid over body with lowering of less than 4 cm (front) or 2 cm (back);
(C) sheet laid so as to mold around the body, with lowering of less than 6 cm (front) or 3 cm (back).

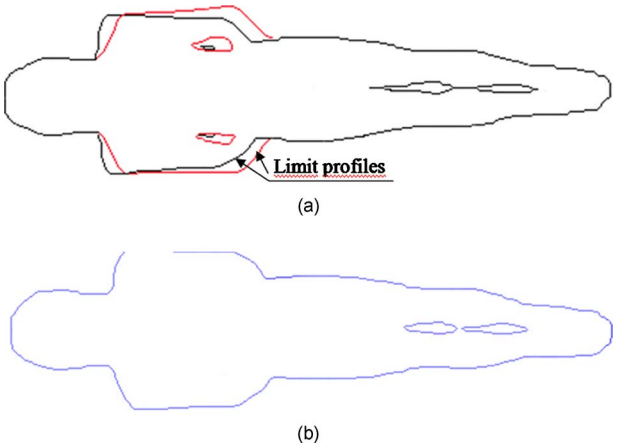

Figure 8. (a) Threshold profiles of front image of TSM according to values shown in Tables III and IV; (b) most probable profile.

As Figure 10 shows, the areas of contact between sheet and manikin correspond to the body image obtained by simple sheet-body contact (condition A).

Some authors[12] believe that the body image formed as a result of contact between sheet and body. Experimental results on a linen sheet impregnated with aloes and myrrh laid on a sweaty, bloodied body show that darker stains form at the point of contact which, from some points of view may be compared with those of the body image of the TS.

However also in agreement with the extreme superficiality of the TS body image that is not coherent with the supposed body fluids imbibition,[29] Fig. 10 also shows that, even in the extreme case (C), the image obtained by direct contact cannot be compared with that of the TS because the latter has image areas where sheet-body contact could not have occurred, e.g., between nose and cheeks, and around the hands.

DISCUSSION OF RESULTS AND EXPERIMENTAL VERIFICATION

The overlap of the n-sheets on the manikin shows, in agreement with Ref. 21, that the front and back images of the TS are distorted due to wrapping of the sheet on the body. In particular, in the case of energy emission,[1] it may be observed that the wrapping of the sheet round the body (Figure 11) causes a distortion of about 10% more with respect to the corresponding dimensions projected on a plane.

As the back image of the TS also shows distortion due to partial wrapping of the sheet, the body of the TSM was probably not laid on a flat surface [Figure 12(a)] but on a curved one, like a trough or stretcher [Fig. 12(b)]. This hypothesis fits the possibility that the TSM was laid on a flat

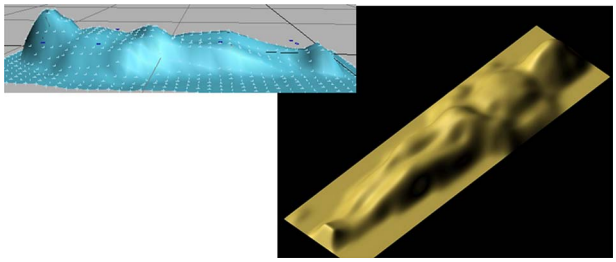

Figure 9. Overlap of front n-sheet on manikin.

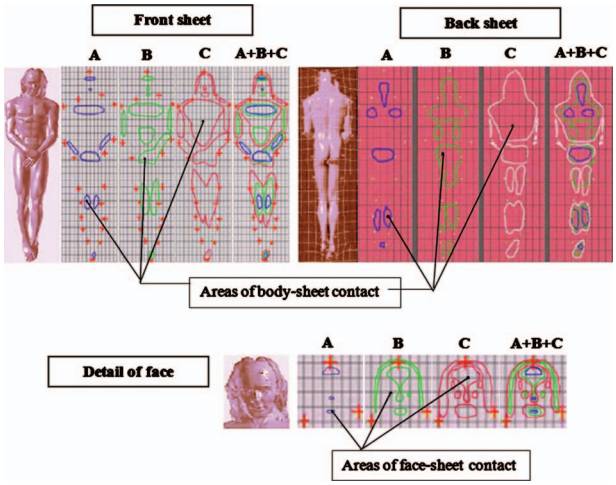

Figure 10. Areas of contact between sheet and manikin, hypothesizing a partial elastoplastic sheet laid on manikin.

surface covered with a layer of soft material like dust of spices. Figure 13 shows that the maximum distance between sheet and body image occurs at segments (A), (B), and (C).

Comparisons between front and back n-sheets with the manikin reveal the compatibility of the front and back TS body image through a three-dimensional (3D) human body, with an uncertainty of ±2 cm. The following information was also obtained:

(i) the anthropometric indexes of the TSM are reliable and the hypothesis that the image on the TS was

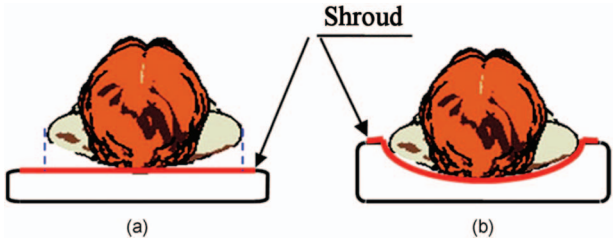

Figure 12. Analysis of back image shows that TSM was probably laid on a curved (b) not flat (a) surface.

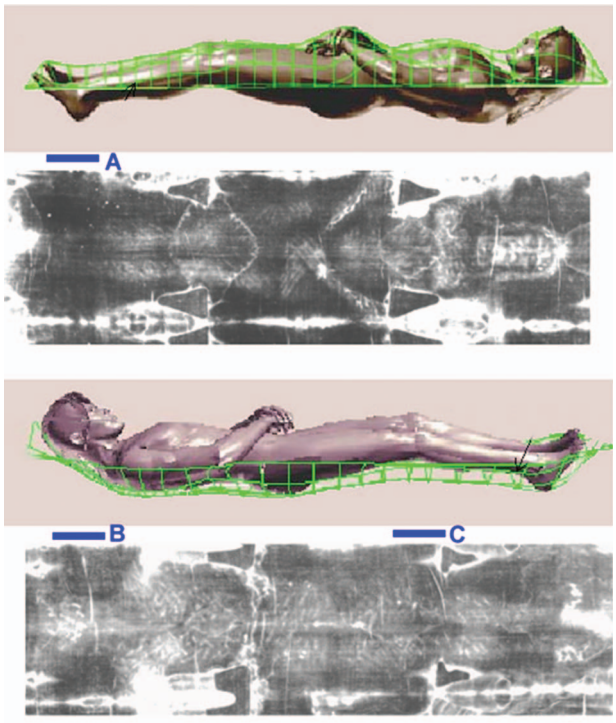

Figure 13. Manikin wrapped in n-sheet and compared with respective image of TS.

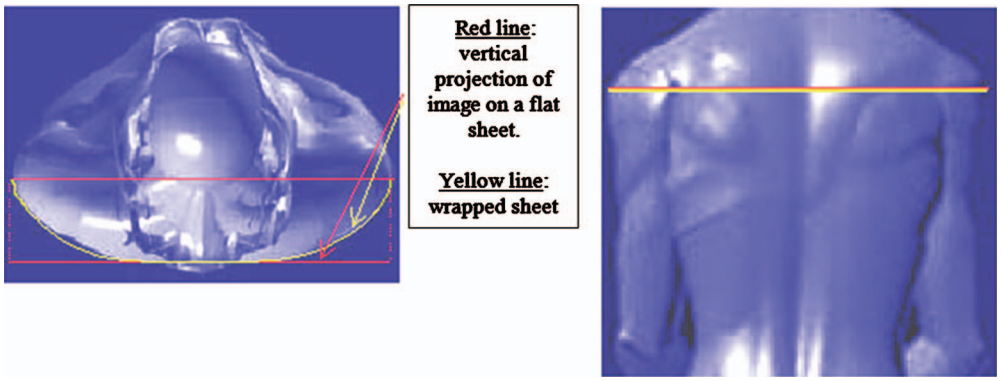

Figure 11. Trunk of manikin viewed from top and back: corresponding image impressed on a wrapped sheet (yellow) is larger, due to effect of wrapping.

Figure 14. From the top, statue in scale 1/2 built from calculations, semitransparent front copy of the TS and overlap of TS copy on statue.

caused by a man being simply wrapped in it is supported;

(ii) the TSM was 175±2 cm tall;

(iii) bone lengths are as follows: humerus: 35±0.5 cm; radius: 26±0.5 cm; femur: 49±0.5 cm; tibia: 40.5±0.5 cm;

(iv) with reference to Fig. 6, the TSM has the following characteristic angles: $\alpha=30\pm4°$; $\varphi 1=10\pm1°$; $\varphi_2=12\pm1°$; $\beta_1=8.5\pm2°$; $\beta_2=10.5\pm2°$; $\gamma_1=11\pm2°$; $\gamma_2=13\pm2°$; $\delta_1=34\pm2°$; $\delta_2=30\pm2°$, indices 1 and 2 referring respectively to right and left arms;

(v) with reference to Fig. 7, the most probable angles of the right upper arm and forearm are $q=47°$, $q'=89°$, and those of the left $q=41°$, $q'=91°$.

This article does not address the problem[30] if the TSM was tightly wrapped by the TS or if he was enveloped in it without lateral bandages, and both the hypotheses survive at the end of the present analysis even if the authors are inclined to think that the TSM was simply enveloped in the TS.

Once determined the compatibility of the front and back TS body image within an uncertainty of ±2 cm, this result was experimentally verified. A statue of the TSM in scale 1:2 was built by Luciano Siviero who used the data resulting from the present numerical study. Also a copy of the TS in the same scale was printed on a semitransparent fabric and the statue was wrapped by this fabric (see Figure 14). The compatibility of the front and back TS body image was therefore experimentally verified.

The statue and the semitransparent copy of the TS was also used to both evidence the noncontact points especially

Figure 15. Face detail of TS transparent copy overlapping on statue. Bloodstains that are in correspondence of hair on the TS copy (red arrows) correspond to cheek and head on the statue. There is also evident the crease due to TS copy wrapping around the face (blue arrows).

in correspondence to the face (see Figure 15). There are also evident the bloodstains in correspondence to hair on the TS copy that correspond to cheek and head on the statue. It is also interesting to observe that folding results in correspondence of the chin and this one is coherent with the so-called "crease below the chin"[9] on the TS that could have been generated during wrapping of the TSM.

CONCLUSIONS

The front image of the Turin Shroud, 1.95 m long, is compatible, with an uncertainty of ±2 cm, with the back image, 2.02 m long because it wrapped a man 175±2-cm-tall. This result was obtained by wrapping a numeric-anthropomorphous manikin, especially constructed by computer, with a digital sheet characterized by anthropometric points detected on the Shroud.

Kinematic analysis carried out reveals the arm position, partially deleted by the Chambéry fire, of the Man wrapped in the Turin Shroud. The human body, characterized by evident *rigor mortis*, kept the position it had on the cross (apart from the arms, which were later folded over the pubic area), with feet stretched forward and downward (at angles of 34° and 30±2°), legs partly bent (knee angles 19.5°, 23.5±3°), and head falling forward (30±4°).

Analysis of the back image also supports the hypothesis that the TSM was not laid directly on a flat surface but on a curved one, such as a trough or stretcher, or on a flat surface on top of a layer of soft material such as dust and/or spices.

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