The Turin Shroud Was Not Flattened Before the Images Formed and no Major Image Distortions Necessarily Occur from a Real Body

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Abstract

We show that, when the images formed, the frontal part of the Shroud of Turin laid on a body in the same position as when the blood stains formed by contact. In other words, after the Shroud was laid on top of a body, no forceful flattening occurred before the images formed. Moreover, the argument that the top half of the Shroud could not have been draping a real body when the images formed – to avoid prominent image distortions – is shown to be incorrect. If a cloth is appropriately laid on the front part of a body, and a body image forms by a vertical projection on the cloth, no major image distortions occur. Small image distortions are to be expected, and indeed we can observe some on the Shroud. These two aspects – the Shroud was not forcefully flattened before the images formed and no major image distortions occur due to the way the Shroud was laid on the body – give the simplest scenario for the formation of the images. There is no need to claim a special event that would have flattened the Shroud before the images formed. Our analysis is based on precise length measurements on digital images, the blood stain locations, and geometry.

1 Introduction

There is currently no well established physical and/or chemical explanation for the formation mechanism of the images on the Shroud of Turin, despite many hypotheses. It is outside the scope of this paper to study them; but as part of this study, we address the following two questions:

1. *Was the Shroud draping the body when the images were formed? More specifically, after the Shroud came in contact with the body to form the blood stains, was the top half flattened before the formation of the images?*

2. *If the top half of the Shroud draped the body when the images formed, should we necessarily expect major image distortions when the Shroud is shown flat?*

There are conflicting statements on this subject in the Shroud literature. Some papers assume that the entire top half of the Shroud was flat during image formation [13]; whereas some others assume or argue that it laid on the body [12, 1, 4]; and others argue that it first came in intimate contact with the body then was partly flattened before the images formed [9, 8, 7].

For example, Mouraviev and Cherpillod [13](p. 127-128), in a speculative hypothesis to explain the Shroud images, write that "radiation of some kind" would be needed "And on condition that the upper length of the cloth was held flat [...]." Although in [12], Mouraviev reverses this statement as he hypothesizes that the Shroud images were formed while the Shroud laid on the body; and that almost no distance would exist between the Shroud and the body – in this case, flatness of the Shroud is no longer assumed.

The necessity to flatten the top half of the Shroud is most often supported by the lack of prominent image distortions. The argument is typically as follow:

> *If the top half of the Shroud were laying on the body when the images were formed, we would see image distortions when the Shroud is unwrapped and laid flat. For example, the face would widen and appear distorted, similar to the distortions of a Mercator projection on a flat surface.*

This argument is no longer clear if we consider the top half of the Shroud covering a body in a loose way. In that case, it does not follow tightly the contour of a body. Its surface is between a body-surface and a completely flat-surface. And, if the width and length of an image body part increase symmetrically, to some reasonable extent, there will be no apparent distortions. It is simply similar to a rescaling of an image – and this shows no distortions.

The distortions depend on the Shroud surface: how close to a flat surface can the Shroud be if it is laid on a body? Also, would there be some cloth buckling creating major distortions? To answer these questions, we analyze quantitatively the possible surfaces of the Shroud laying down on a body and the resulting projections once it is flattened. We will show that a sheet surface can be compatible with all the blood stains made by contact and create no major image distortions. Moreover, there appear to be small image distortions coherent with the Shroud loosely laying on a body when the images formed. Some image distortions have been previously reported [1]. We present reproducible length measurements to further support these and detect some other ones around the face.

We will also show that – if it were needed – the Shroud cannot have been lifted up from the body to be forcefully flattened before the images formed. That is, the Shroud cannot have been globally repositioned over the body in order to be made flatter to avoid major image distortions. Essentially, this is based on the locations of several blood stains and the fact that if flattening were needed, it would have moved several of these blood stains outside their natural locations. This is analyzed in Section 3.

These conclusions are important for the following reasons. First, it offers the simplest scenario for the formation of the images. For example, there is no need to have a forceful flatenning of the Shroud; and there is also no need for some objects surrounding the body to maintain the Shroud flat. The images can form while the Shroud draps the body – with no "flatenning event." Second, the fact that the Shroud cannot have been made flat – and there are very strong indications of that fact which makes it easy to demonstrate – may lead some to conclude, since there is no major image distortions seen on the Shroud, that no *real body* could have formed the images by a vertical projection. For example, some may conclude that a bas-relief was used to obtain two such apparently contradictory facts. The reasonning might be as follow: The Shroud was not flattened, therefore a shallow artificial artifact (e.g. bas-relief) was used to create the images to avoid image distortions. This paper shows that this reasoning is incorrect: the Shroud was not flattened, yet a real body – assuming a simple vertical projection – can have made these images without creating major image distortions.

We use two different approaches to study the possible image distortions: real body cross-sections with a modeled sheet in Section 4; a real body and real linen gridded sheet, using a digital overlay technique for precise length measurements, in Section 5.

Our conclusion and future work are in Sections 6 and 7. The next section addresses some preliminary aspects.

2 Preliminaries

We will do many digital length measurements: we explain the technique used in this section. We also use some important assumptions that we address explicitly in the next sub-section.

2.1 Our major assumptions

Throughout this paper we assume the following:

1. The Shroud was covering a full human body form (henceforth simply "body") that was lying down essentially perpendicular to the force of gravity when the blood stains and images formed.

2. The images formed by a mechanism that reproduces each point by a vertical projection, from the body to the Shroud.

3. The distance between the surface of the body and the Shroud is inversely proportional to the luminance of the image. More precisely, we will assume that beyond two centimeters the projection has lost more than 80% of its efficacity.

Notice that the last assumption does not give an explicit relation between the distance sheet-body and the luminance, but a constraint on this relation.

Our analyses assume a "straight vertical projection," from the body, to form the images. Several other projections have been analyzed [1]: perpendicular to the sheet, perpendicular to the skin and non-collimated (dispersive). Ercoline et al. [1] argue that the vertical projection avoids most image distortions whereas the others do not (see also [4]). We agree that the vertical projection should create the least amount of image distortions (among the abovementioned projections).

On the other hand, we conjecture that the projection direction and value (its "force") is probably due to only one rule: the distance attenuation of the projection. That is, every point of the body might be projected by following the shortest path to reach the sheet. That would be a simpler rule unifying the direction and force of the projection. This projection would be perpendicular to the skin or sheet in some cases – for example when the sheet and body surface are flat and parallel. On some other configurations, it would not be perpendicular neither to the skin nor to the body surface. It is beyond the scope of this paper to analyze this conjecture.

Notice that all the projections just mentioned give almost identical results if the sheet-body distance is small (i.e. < 1cm), and the body is not near vertical, since the Shroud image resolution is small (about 5mm). So, as a first approximation, the vertical projection is close enough for this study.

The rule of attenuation of this projection is also rather unknown. Some candidate laws, parameterized by the distance sheet-body, are: inverse square, inverse exponential, and inverse linear. Actually, we will simply assume that beyond two centimeters, the projection has no longer any significant effect.

Henceforth we will use for the image formation mechanism, as an adequate approximation for our analyses, a straight vertical projection from the body to the sheet with a reach of essentially two centimeters.

2.2 Digital length measurements

We use a simple technique to report length measurements that can be **reproduced**. It is based on publicly available digital images of the Shroud and the use of a graphic software which can measure the number of pixels between two points. A web-based software to do length measurements is also available at [6] where one of several digital photographs of the full Shroud can be selected. We report all length measurements on the Shroud that are used in the rest of this paper in Tab. 1 based on the frontal part of 1931 photograph of Enrie, as displayed in Fig. 1. To make the paper self-contained, we present its calibration and discussed its uncertainty.

As can be seen from Tab. 1, the lengths are calculated using the number of pixels between two end-points. An end-point is a (x, y) coordinates directly taken from the digital photograph. Its left upper corner has coordinates $(0, 0)$. The x coordinate grows rightward; the y coordinate grows downward. Its calibration of 1px=1.901mm is based on the width of 1103mm and 580 pixels from $(16, 2191)$ to $(596, 2191)$ (near the bottom of the frontal image). The uncertainty of the number of pixels between these two points is ± 1, i.e. a variation of less than 0.4%, a negligable uncertainty for the application of this paper. Since we do not know the exact end-point locations where the reported length was taken, we also need to consider the variation in number of pixels along the sides of the Shroud. Drawing two line segments on each side we could not see a variation of more than five pixels, which keeps the uncertainty below 1%. If we assume that the reported length has an uncertainty of ±5mm, the calibration has uncertainty of less than 0.009mm per pixel. Finally, the camera used could have some small edge deformations, but these appear undetectable.

A few remarks about the measurements themselves: measurement I is a little less than half the head height H, in line with a real human head (see Fig. 5); the head and width measurements are larger than the body model used in our experiment (see Section 5). This tends to show that a projection on a curved surface occurred. The narrow appearance of the face is due in part by the the darker stripes on each side of the face.

3 A Flattening of the Shroud?

In this section we analyze the longitudinal and lateral alignments of the blood stains with the images of the Shroud to show that, if it were required to avoid major image distortions, the top half of the Shroud cannot have been lifted from the body and forcefully made flat before the images formed.

Many blood stains were due to contact of the body with the sheet. For instance, in Fig. 2, blood stains labeled A, B, and E are due to contact with the body. On the other hand, blood stain F is clearly outside the body image although Lavoie et al. [9] proposed that it was done by contact. It appears that the "blood stains" C were not done by contact, but are images of blood stains [3].

Nevertheless, blood stains B, C, and D (or images of blood stains) stop at the edges of the arms: a small – as little as 5mm – longitudinal movement of the Shroud would have thrown them outside the image. For example, either blood stain B would come below the arm, or stain D would come above the arm. Likewise, the blood stain A, most probably due to the wrist wound, would no longer be centered properly at the wrist and look awkward. We can only conclude that the Shroud did not move from that point between the creation of the blood stains and

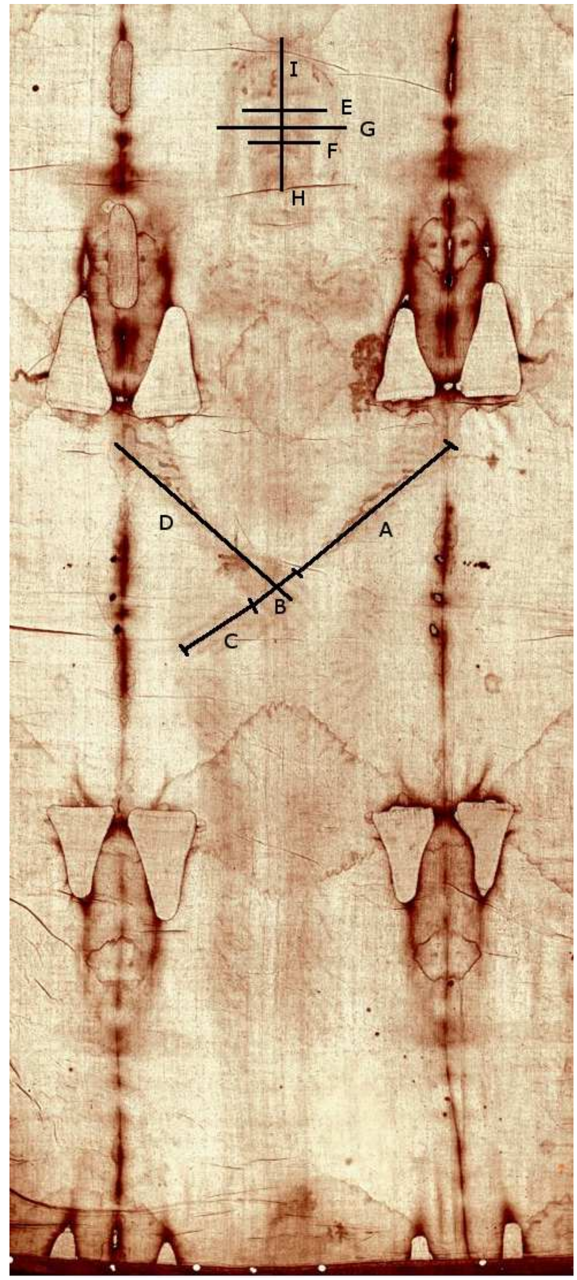

Figure 1: **A view of length measurement locations as reported in Tab. 1 based on the top half (frontal) part of the 1931 photograph of the Shroud taken by Enrie.**

Label	Description	End-points coordinates	Nb of pixels	Length in cm
A	Right forearm	$(455, 1603)(323, 1713)$	172	32.6
B	Left hand width	$(282, 1743)(322, 1713)$	47	8.9
C	Right fingers	$(283, 1743)(224, 1781)$	70	13.3
D	Left forearm and hand	$(164, 1600)(316, 1735)$	203	38.9
E	Width of face, eyes	$(275, 1310)(346, 1310)$	71	13.5
F	Width of face, tip nose	$(280, 1338)(340, 1338)$	61	11.6
G	Width of face-hair	$(253, 1325)(363, 1325)$	111	21.1
H	Head height	$(308, 1379)(308, 1248)$	132	25.1
I	Top head to center eyes	$(311, 1248)(309, 1309)$	62	11.7

Table 1: **Length measurements on the Shroud, used in this paper, based on a digital version of the 1931 photograph of Enrie. The calibration of this photograph is 1px=1.901mm. The end-points give the absolute (x, y) coordinates of the measurements for that particular digital photograph. These can be verified using many popular graphic software (e.g. Gimp [17]), and also through the web-based online tool at [6]. Obviously, these do not necessarily measure the corresponding body parts but measure their (possibly distorted or scaled) projected images on the Shroud. See Fig. 1 for a view of the measurement locations.**

the formation of all other images.

Moreover there are blood stains made by contact in the face area, as can be seen in Fig. 3. If these had been moved up from a lower position, that is they were lower and went up due to a putative flattening, they would have been in an odd location. In particular, the ε-shape blood stain would had been over an eye – this is not explainable in terms of contact at that location.

In summary, a (re)flattening of the Shroud to avoid major distortions would assume that it was sagging at some places, and once flattened would have moved up or down the blood stains of the arms and face. Since the blood stains of the arms do not appear to have moved at all, and the blood stain of the face do not seem to have been created several centimeters lower, we have to conclude that there was no longitudinal flattening of the Shroud once the blood stains formed.

This conclusion is in line with the property of the blood stains found by Lavoie et al. [10]: they appear undisturbed. On the other hand, our argument differs to the other work of Lavoie et al.[9, 8] where they argue in favor of a first intimate contact of the sheet with the body – at least for the face and arms – and

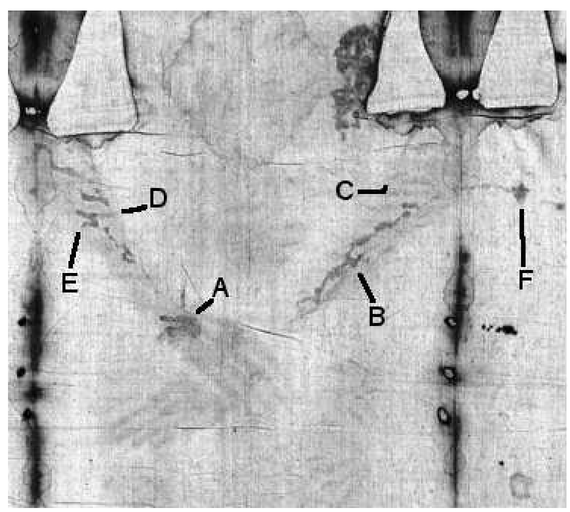

Figure 2: **Some blood stains are right to the edges of the arms (e.g. C and D).**

Figure 3: **If the ε-shape blood stain had been lower by a few centimeters, it would have been over the eye – a very odd location.**

then a partial flattening of the Shroud for the face and near one of the elbow where an off image blood stain appears.

We think that it is possible that the blood stains seen around the face was formed by contact from their apparent location. Otherwise, if we agree with the experiment presented in [8], that would imply that no blood stains could have been formed from the hair while the Shroud was pressed tightly around the face since we do not see any blood stains outside the hair area on the Shroud. We also think that the off image blood stain near the elbow could have been caused by a few drip of bloods along the Shroud dangling from the side.

4 Cross-section Projections

In this section we analyze the projection of two cross-sections of a body onto a modeled sheet. We will show that – for the image areas as seen on the Shroud – only small distortions could occur. The modeling of the sheet is simple, but we believe it is realistic enough to show obvious image distortions. In this section, for the face, we focus on showing that a symmetrical enlarging, i.e. a scaling, of its image is mostly occurring if the sheet is flattened after the images formed.

All the cross-sections used were derived from a real body. They were produced by the Human Visible Project. Barrodale Computing Services has made these images available via an interactive web-based interface called the *Grid Slicer Demo* [11]. It can extract any slant of slices – in particular lateral and longitudinal slices. The resolution of these images is one pixel per one mm.

4.1 Modeling the sheet

Sheet modeling is complex. It has been studied by many researchers with various degrees of success [2, 14]. Weil [15] pioneered such work by using the catenary function: $y(x) = a\cosh(x/a) = a(e^{-x/a} + e^{x/a})/2$ where a is the tension, scaled to the density of the sheet. We believe that using such a model would only obscure the results as physical reality depends largely on the tension used. In this section, our sheet analyses involve only body cross-sections. The sheet appears as a hanging cable. As can be seen from the exponential form of the y function, the curve forms almost a straight line near the tension point if a is large enough. Consequently, over a short length, a straight line will be our model for the sheet: we use several straight lines to model the cross-section of the sheet spanning several touching points.

4.2 Head cross-section

One of the most complex surface area is the face with hair: there are many height variations in a relatively small area; that is the sheet-body distance varies in proportion to the surface distance. We concentrate our cross-section analysis on that area.

Fig. 4 shows two superimposed cross-sections of the head with a simplified sheet model. Each cross-section is actually a contour created from cross-sections of a real head. These contours were drawn by a computer program based on more than forty points extracted from the cross-section slices. All lengths reported in this section are based on calculations and not the grid itself which is a quick tool to verify them.

A possible sheet covering the cross-section at the tip of the nose is also shown as a dashed line. Notice that this sheet is supported, among other parts of the face, by the forehead, drawn as a dotted line, and the nose which is 7mm above the forehead. This explains the height of the sheet compared to the cheeks: the sheet slants slightly from the forehead down toward the cheeks, without touching them. Even though it is not shown on the diagram, the sheet goes down on the surrounding surface, and due to friction, holds both sides under tension.

The sheet model has two segments on each side, but only the symmetrical segments A and A′ receives an image projection from the underlying segment across the nose tip. When the sheet is flattened they form part of the image of the face. The end-points of these two segments have been determined by the distance sheet-body – that is due to the attenuation of the projection passed two centimeters – and by the location of the eyes. Based on the Shroud, there is a drop in image formation passed the eyes at the level of the nose tip. This is a similar projection.

Segments A and A′ have the same length: 6.0cm. The projection of the segment underneath them has length 11.3. That is the flattening would give a widening of about 7mm. This is a small amount compared to what is obtained in the next section. But we will show using Fig. 5 that the amount of lengthening is similar: this avoids distortions.

In Fig. 5, we have a longitudinal cross-section of the same body area. The image projection considered is made of the segments B to E. The sum of their length is 23.3cm; this is the flattened projection length of the underlying segment of the face which is 21.5cm. The flattening would increase the length by 1.8cm. As we can see, this is in proportion to the 7mm increase over 12cm. The increases are certainly small: this is mainly due to our simplified sheet model which does not include sagging of the cloth. But the important point to notice is that lengthening and widening in the region of the face, occurs symmetrically, creating a scaling rather than a distortion.

The next section presents a more realistic experiment by using a real model and a real linen sheet.

5 Real Sheet Projection

In this section we based our analyses on a real linen sheet covering a real body, using a technique of transparent digital images. As in Section 4, we address the issue of small distortions vs major distortions of the images. We have used a linen sheet of the same width as the Shroud, although its length is only 3/4 of it since we only needed to recreate its top half. Our sheet has an imprint of a grid – this allows us to measure body projections on the sheet.

Fig. 6 presents four photographs. The original digital photographs reproduced in this section are available at [5]. These can be downloaded to verify the reported measurements.

We are mainly interested in the photographs with the sheet covering the body. But to locate where the body images would form – as if rays from the body were projected vertically onto the sheet – we also need the precise location of the body underneath the sheet. This can be done by superimposing the sheet photograph, making it digitally transparent, over the corresponding body photograph. The digital transparency does not otherwise alter the photographs – and this superposition is not a direct representation of possible distortions – but allows us to measure them, if any. This can be done with many popular graphic software. We have used Gimp 2.2.4 [17] for this and all length measurements. Fig. 7 shows the results.

From these photographs, we cannot infer the precise body-sheet distances. But, when taking the photographs we could easily verify a few important points about them: the sheet was in contact with the top edges of the forearms, the top edge (knuckles) of the left hand and its fingers. The tip of the nose was in contact with the sheet, as well as most of the fore-

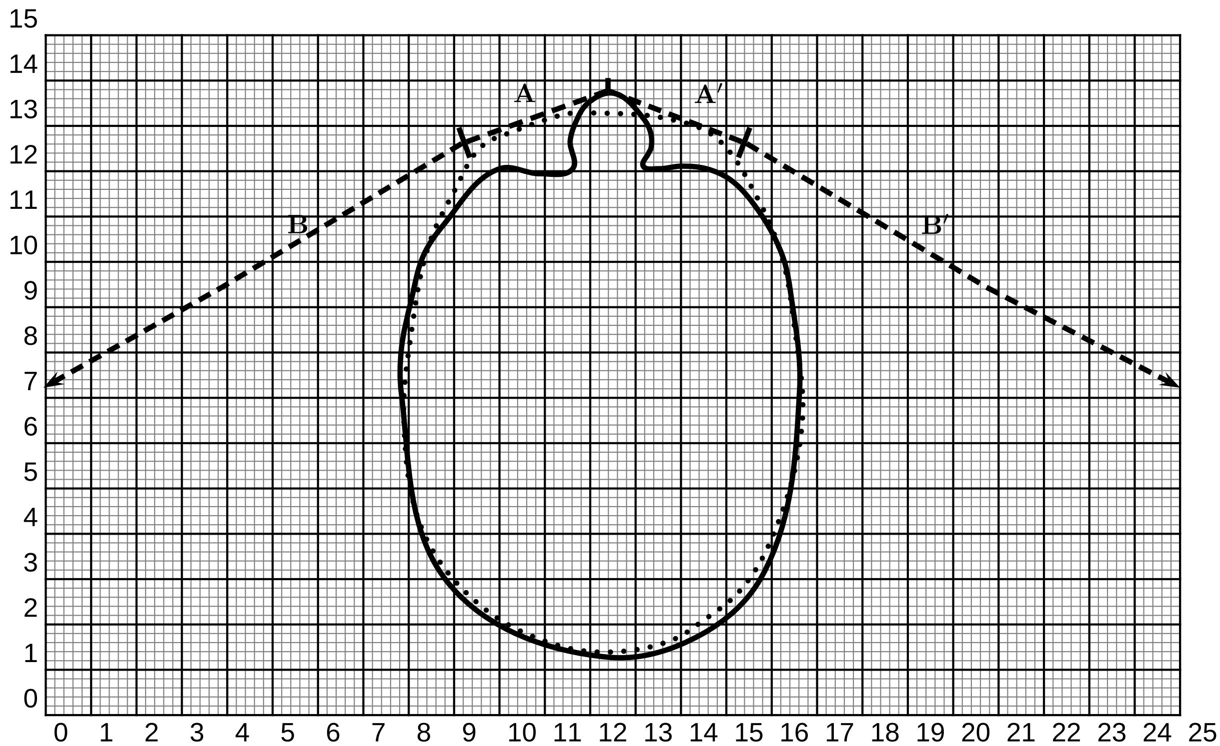

Figure 4: **Two superimposed cross-section contours of the head based on real body cross-sections from the Human Visible Project: at nose tip (solid line) and right above the eyebrows (dotted line). A simplified sheet model cross-section at the nose tip (dashed line), in two segments on each side: only the segments A and A′ receive an image projection. Each major grid division represents 18mm. Most measurements can be done directly on this diagram using that grid. For example, the depth of the head from the back to the nose tip can be measured at 22.2cm, ±3mm. The cross-section locations can be seen in the longitudinal cross-section of Fig. 5.**

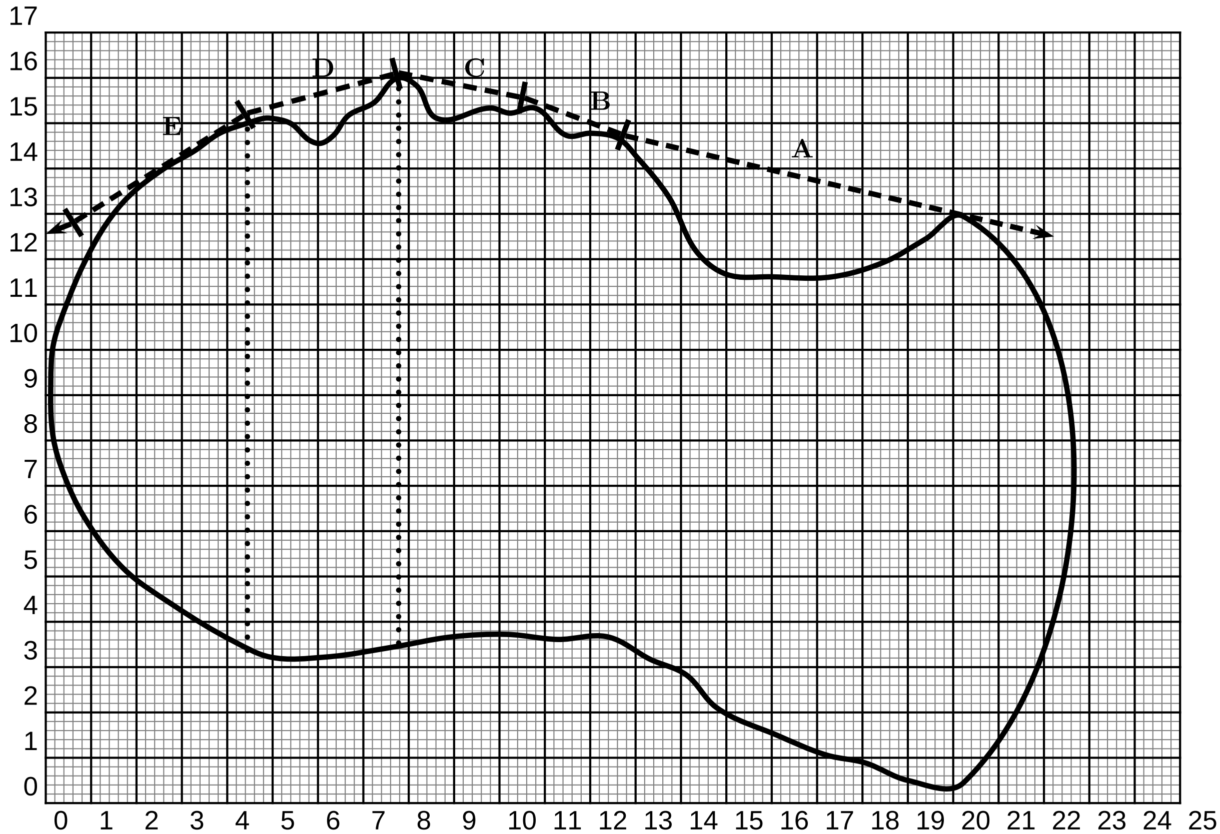

Figure 5: **A longitudinal cross-section contour based on the same real human body as in Fig. 4. The sheet is modeled by five straight line segments, represented by dashes, labeled A to E, although A is not used in the calculation for possible distortions. The grid is similar to Fig. 4, with one major division representing 18mm. As in Fig. 4, the depth of the head from the back to the nose tip can be measured to 22.2cm, ±3mm. The height of the head, i.e. from chin to top of head, that is from** $x = 12.5$ **(the** x **coordinate of the beginning of segment B) to coordinate 0, is** $12.5 \times 1.8 = 22.5$**cm, ±3mm. The length from the center of the eyes to the top of the head is 10.8cm; so the ratio with the height of the head is** $10.8/22.2 = 0.486$**. Notice that this is similar to the same ratio as the Shroud of Turin, namely,** $11.7/25.1 = 0.466$ **(see Tab. 1). The two dotted lines represent the cross-section locations shown in Fig. 4.**

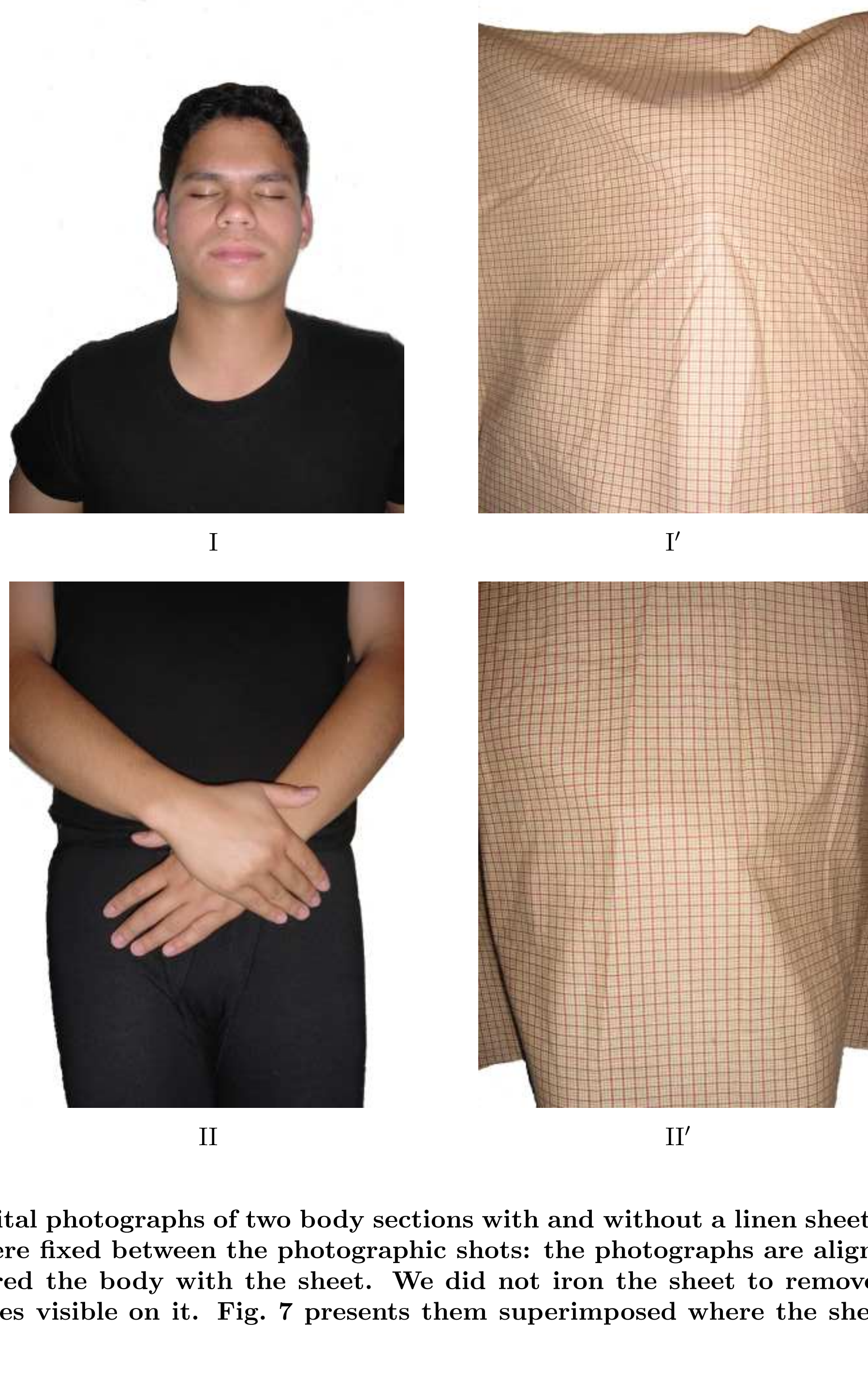

Figure 6: **Digital photographs of two body sections with and without a linen sheet. The camera and body were fixed between the photographic shots: the photographs are aligned. Only one person covered the body with the sheet. We did not iron the sheet to remove some of the small wrinkles visible on it. Fig. 7 presents them superimposed where the sheet is digitally transparent.**

head. The chin was not in contact with the sheet, although very close to it, i.e. a few millimeters; similarly for the cheeks although with an apparent 1cm distance. In summary, although it differs in some details as explained in the next paragraph, the sheet covers the body compatible with the obvious blood stain locations of the Shroud.

Notice that we have not tried to be precisely as the Shroud of Turin in terms of body configuration and aspect. For example, the fingers of both hands are extended, but this is not the case for the Man of the Shroud. Our goal is to be close enough without assuming that only one configuration of the body is possible. For example, it is obvious that the Man of the Shroud has both hands crossed, but the exact vertical positions of his elbows are not obvious. Also, for the sheet covering the arms and hands, we can notice from the photograph that the sheet ends near the knees as the lateral edge can be seen on the photograph. This shortness of the sheet created less tension on its edges near the knees, resulting a more tuck aspect of the sheet then it would have been if we had extended the sheet down the feet.

A major division of the grid seen on the sheet is almost 1cm square. More precisely, direct measurements on the sheet show that it is rectangular: for 30cm (±0.2cm), the flat sheet spans 29 grid divisions lengthwise but spans 27 grid divisions widthwise. So, a major grid division is 30/29cm by 30/27cm, i.e. about 1.034cm (±0.0068cm) by 1.111cm (±0.0074cm). The diagonal of one rectangle is $\sqrt{(30/29)^2 + (30/27)^2}$, i.e. about 1.518cm. These measurements are used to evaluate the degree of image distortions that would be generated if the sheet of Fig. 7 were made flat. This is analyzed separately for photographs I and II in the following sub-sections.

5.1 Head area

We can calibrate the photograph of Fig. 7 I by measuring the number of pixels across several divisions near the center of the image. From pixel (709, 936) to pixel (906, 929), i.e. 197px (±2), we have four widthwise grid divisions of 1.111cm each: 1px= 0.225mm (±0.002mm). This is confirmed by a longitudinal measurement in the vicinity of these points and by

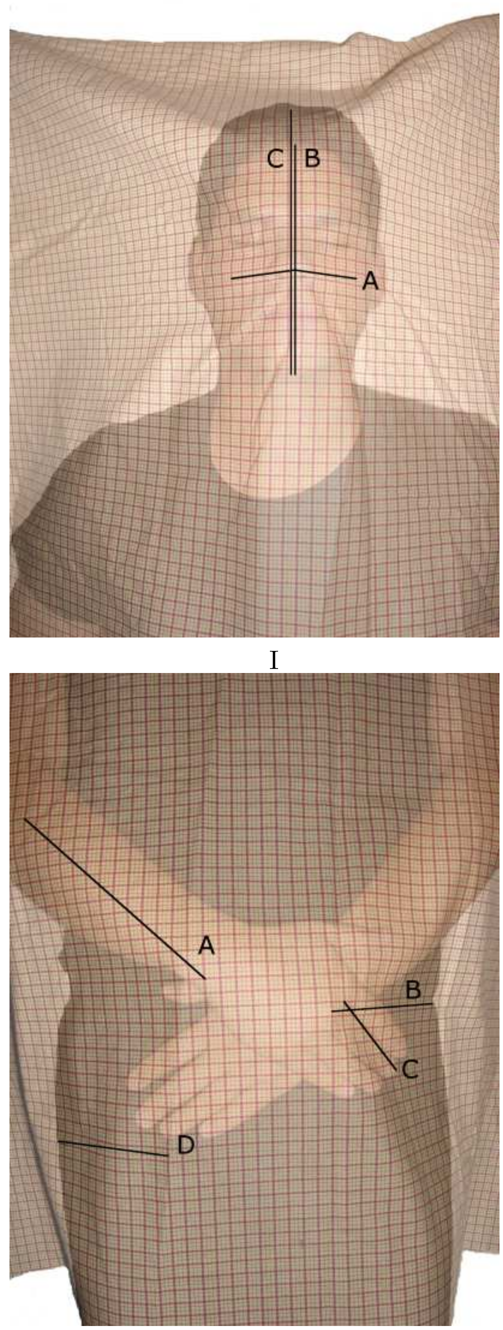

Figure 7: **The sheet photographs of Fig. 6 made digitally transparent over the body. The lines show measurements reported in Section 5.**

Description	Label	End-points	Px (x)	Length cm	Grid Length cm
		Measurements on Fig. 7 I		$x \times 0.225$	
Face width at nose tip	A	$(696, 923)(894, 896)$; $(895, 896)(1086, 922)$	393	8.8	12.2
Face height	B	$(895, 505)(895, 1223)$	718	16.2	19.4
Head height	C	$(882, 1222)(882, 396)$	833	18.7	25.8
		Measurements on Fig. 7 II		$x \times 0.228$	
Right forearm	A	$(47, 456)(613, 959)$	756	17.2	19.7
Left hip	B	$(1011, 1061)(1324, 1037)$	313	7.1	12.2
Middle finger	C	$(1048, 1031)(1213, 1245)$	270	6.1	8.9
Right hip	D	$(153, 1468)(496, 1514)$	346	7.9	12.2

Table 2: **The length measurements done from the digital photographs of Fig. 7. By direct measurement on the sheet: one lengthwise grid division is 1.034cm**± 0.0068**, and one widthwise grid division is 1.111cm**± 0.0074**. Calibration of photograph I is 1px**$= 0.225$**mm; photograph II is 1px**$= 0.228$**mm. A grid division is 1.034cm long by 1.111cm wide; so, a diagonal is 1.518cm.**

a direct measurement of the width of the model face at the tip of the nose (12.0cm$\pm$0.3) whereas the measurement from $(614, 899)$ to $(1141, 899)$, 527px, gives $527 \times 0.225 = 11.8$cm.

Measurement of the width of the reproduced face segment along the nose tip, from $(696, 923)$ to $(894, 896)$ and from $(895, 896)$ to $(1086, 922)$ (line labeled A), a total of 393px, gives $393 \times 0.225 = 8.8$cm. This body segment projects to a sheet segment of 11 grids, that is $11 \times 1.111 = 12.2$cm. So, the width increased by 3.4cm. The similar measurement F for the Shroud (Fig. 1, Tab. 1) gives 11.6cm, a difference of 6mm from our own experiment.

If we measure the height of the face from the tip of the chin to the top of the forehead near the borderline of the hair, that is from $(895, 505)$ to $(895, 1223)$ (line labeled B), 718px, we get 718×0.225mm= 16.2cm. The projection of that segment on the sheet covers 18.8 grids, that is $18.8 \times 1.034 = 19.4$cm. The projection increases the height by about 3.2cm.

If we measure the height of the head from the tip of the chin to the point of image reproducibility near the top of the head, that is from $(882, 1222)$ to $(882, 396)$ (line labeled C), 833px, we get 833×0.225mm= 18.7cm (direct measurement on the model gives a head height of about 21cm, this difference is due to the missing part of top head not reproduced by projection). The projection of that segment on the sheet covers 25 grids, lengthwise, that is $25 \times 1.034 = 25.8$cm. The projection increases the height of the head by about 7.1cm. Notice that the height 25.8cm is similar to the Shroud head height of 25.1cm, measurement H (Tab. 1).

The height and width of the projected head image have increased almost symmetrically: by about 3.4cm widthwise over a length of 12.2cm (28%); 3.2cm over 19.4cm (16%), and 7.1cm over 25.8cm (27%). For our experiment, the center of the face would appear slightly out of scale (i.e. 1cm too wide, as $2.2/12.2 = 18\%$) compared to the face, but not compared to the overall head.

The possible image distortions due to cloth buckling can only come from the four segments that can be seen in Fig. 7 I: two heading diagonally upward from the eyebrows, and two heading diagonally downward from the nose tip. It can be seen that the major cloth buckling from the eyebrows are mostly outside the image area. The edges of these cloth buckling, over the face area, occur only across the width of one grid rectangle. This can distort the image by a few millimeters – it would be insufficient to be detectable on the Shroud.

In summary, the head of our model is projected on the sheet with an increase of height and width almost at the same rate – with just a few asymmetrical millimeters off – which makes image distortions difficult to perceive. The image of the face on the Shroud has been projected in such a way that it appears wider and taller than our real model (by about 22%) – this is in line with an increase in scale due to a projection on a sheet surface laying downward on each sides of the face. Moreover, no prominent distortions due to cloth buckling occur in this experiment.

5.2 Arms and hands area

The calibration of Fig. 7 II should give almost the same result as Fig. 7 I. It can be slightly different since the depth of the head can be slightly different to the depth of the body at the level of the hands. Indeed, a calibration over five grids gives 1px= 0.228mm: widthwise from $(711, 978)$ to $(955, 967)$, 244px, which is $5 \times 11.11/244 = 0.2276$mm; and lengthwise from $(831, 904)$ to $(840, 1130)$, 227px, which is $5 \times 10.34/227 = 0.2277$mm. By averaging and rounding to the third decimal we get 0.228mm per pixel.

Measuring part of the right forearm from $(47, 456)$ to $(613, 959)$ (line labeled A), 756px, we have 756×0.228mm= 17.23cm; it covers 13 grid diagonally, that is $13 \times 1.518 = 19.7$cm. This slight lengthening of about 2.5cm is not due to the projection of the forearm onto the sheet (since the sheet touches the forearm along that measurement). Its is rather due to the apparent closeness: if the sheet were flattened and brought forward with the rest of the top of the body it would appear longer.

By simply looking at Fig. 7 II, the most probable source of image distortion is from the hip, on the left side of the body (i.e. on the right of photograph), since the sheet makes a substantial down change of gradient after the knuckle of the middle finger. Indeed, from point $(1011, 1061)$ to $(1324, 1037)$ (line labeled B), there are 313px, i.e. 313×0.228mm= 7.13cm; but this spans 11 lateral divisions, that is $11 \times 1.111 = 12.22$cm: if the sheet were flattened, the right hip would appear 5.1cm wider. This is confirmed by Ercoline et al. [1] for the Shroud (see also Jackson [4]): a statistical analysis shows that the body image of the Man of the Shroud, at hip level, is wider than normal by several centimeters.

The right side hip (i.e. on the left side of the photograph) shows also some possible widening. From $(153, 1468)$ to $(496, 1514)$ (line labeled D), a length of 346px, that is 346×0.228mm= 7.89cm; it projects on 10.8 grids, widthwise, so that once flattened it would be $10.8 \times 1.111 = 12.2$cm. This is an increase of about 3cm – not a prominent widening considering the width of the whole body.

There are no other major cloth buckling, which makes image distortion almost undetectable.

Notice that the sheet almost follows the fingers of the right hand. If the sheet were flattened – and the fingers made a vertical projective image on the sheet – the image of the fingers would have almost the same length as if they were straight. The apparent distortion is a lengthening of the fingers. We can verify this fact on the photograph: the middle finger apparent length is 6.1cm: measured from $(1048, 1031)$ to $(1213, 1245)$ (line labeled C), that is 270px. This spans 5.9 diagonal grids, which gives $5.9 \times 1.518 = 8.9$cm. The middle finger of the right hand is 10cm, as measured directly on the model. So there is an apparent length increase of this finger by about 2.8cm.

Notice also that if the fingers of the left hand had been closer to the edge of the thigh – for example, by lifting the shoulders up – an apparent lengthening, *compared to the real fingers*, would have occurred since a projection of the straight fingers on the slanted sheet would have happened. This would have been quite similar to the apparent long extended fingers seen on the Shroud.

In summary, measurements show that no distortions can be markedly perceived if the middle part of the body is projected on the sheet. Some observable widening of the hip is expected – it has been measured at 5.1 centimeters on one side in our experiment – and such an apparent widening has been observed for the Shroud by the work of Ercoline et al. [1].

6 Conclusion

It was shown that, once the blood stains formed by contact, the top half of the Shroud could not have been lifted up to be flattened to avoid major image distortions. After the blood stains formed, the Shroud essentially stayed in the same position prior to the image formations. It is not impossible that some local movement of the Shroud occurred, for example near its edges or the face. Although, there are no strong evidences in that direction.

It was also shown that a flattening of the top half of the Shroud is not required to avoid major image distortions. That is, there exists some natural way for the Shroud to lay on the body while the images are formed without causing major image distortions – albeit the Shroud had to be laid carefully over the body. Moreover, it appears that there are some small image distortions, coherent with the Shroud laying on a human body form. This covering is also consistent with the known blood stain locations on the Shroud.

We have also conjectured that the mechanism of projection is probably neither normal to the skin, nor to the sheet, and not really perpendicular to gravity, but is probably following the shortest path to the sheet. Further research is necessary to conclude on this aspect.

7 Future Work

To further analyze the possible image distortions, it would be most useful to do several real human body 3D scans, with and without a covering sheet. Commercial 3D full body scanners (e.g. made by Cyberware [16]) have enough resolution (e.g. 1mm) to allow a more experimental approach to the study of image formation of the Shroud. Such work could produce several examples of surfaces of a sheet covering a body. From two surfaces, one from the body and the other from the sheet covering it, a complete analysis of possible luminance variations and image distortions could be precisely analyzed. It would be possible to investigate how easily, or difficult, it is to lay down a sheet on a body to produce only small image distortions. Moreover, from such precise surfaces it would be possible to simulate the possible physical mechanisms that created the Shroud images – including the verification of the conjecture mentioned in the conclusion.

It would be useful to determine – by a direct visual observation on the Shroud or from a very high resolution digital image of it – if there is a clear chemical or physical distinction between the blood images. That is, which blood stains – as seen on the Enrie photograph for example – are really due to contact? It is most likely that some are due to contact and others by the imaging mechanism. This distinction should help to investigate the draping of the Shroud. This was also proposed by Jackson [3].

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