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A comparison of measurement reliability between a sonic digitizer and a tape measure on a complex three-dimensional object

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A COMPARISON OF MEASUREMENT RELIABILITY BETWEEN A SONIC DIGITIZER AND A TAPE MEASURE ON A COMPLEX THREE-DIMENSIONAL OBJECT

An Abstract of a Dissertation

Submitted In Partial Fulfillment of the Requirements for the Degree

Doctor of Industrial Technology

Approved:

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ABSTRACT

Digitizers and scanners have begun to replace traditional devices for measuring three dimensional objects. However, there is a shortage of relevant research to compare digitizer tools with other measuring devices. The objective of this study was to compare the measurement reliability of a sonic digitizer to a traditional measuring tool, the tape measure, for measuring a complex, three-dimensional object. It was hypothesized that:

H_1 Data from measurements with the digitizer vary less than data from measurements with a tape measure at the 0.05 level of significance.

H_2 The data from eight complex surface measurements taken with a digitizer vary less than data from a tape measure at the 0.05 level of significance.

Locations on a complex three-dimensional object which replicated a human body (a half-size dress form) were selected for measurement. Measurements were made by individuals who had experience in measuring the human body with a tape measure.

The digitizer was a more reliable (i.e. showed less variability) measurement tool than a tape measure for five measurement locations on the complex object, especially for the object's poorly-defined areas. Measurement data from one location with body landmarks (center front) had less variability with the tape measure than with the digitizer tool.

The measurements with the two tools did not show overall differences in mean values (tool x location) when examined with a two-way analysis of variance. However, when using the Levene's ANOVA Transformation, variances of location and tool by location effects were significant. Based on the statistical analysis, both hypotheses were supported by the results and were accepted.

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CHAPTER I

INTRODUCTION

Digitizers and scanners have begun to replace traditional devices for measuring three-dimensional objects. However, there is a shortage of relevant research which compares digitizer tools with other measuring devices. Various operators who had not previously used a digitizer but were familiar with other tools might find the new device more reliable. The objective of this study was to compare the reliability of a sonic digitizer to a traditional measurement tool, the tape measure, for measuring a complex, three-dimensional object, a one-half-size dress form.

Statement of the Problem

The problem was to determine whether complex object measurement data obtained with a digitizer were more reliable than measurement data obtained using a tape measure. Measurements taken included the waistline, hipline, left hipline depth, back hipline depth, right hipline depth, front hipline depth, center front, and center back of the one-half-size dress form.

Statement of Purpose

The purpose was to compare measurement data to determine if a modern tool was more reliable than a traditional tool for measuring a complex, three-dimensional object. The tape measure has been a traditional measuring device, but as technology has evolved and instruments have become less expensive, modern tools such as digitizers and scanners may provide a better alternative of measurement.

Statement of Need

Based on previous studies, the traditional measurement tool, the tape measure, is known to have a small amount of inherent error. The measurement reliability using a tape measure is dependent on the original accuracy of the tape measure, the resolution of the graduation lines, the tautness when holding the tape measure, the angle of direction from which the graduations are read (Farago & Curtis, 1994), and the position placed (Staples, Pargas, & Davis, 1994). Yoon (1992) reported that with a tape measure, the human body hipline measurements were under measured an average of 4.54 cm. This error in measurement can be reduced with a three-dimensional digitizer and scanner.

Apparel Sector

For a more competitive United States textile industry, focus should be on the custom fitted and speedy delivery of garments. These two factors would assist manufacturing in the United States and thus reduce importation from overseas such as China.

The apparel sector may be able to benefit from research with digitizers and scanners. The apparel industry is the sixth largest industry in the United States (Off, 1995) and it serves disabled persons, government and emergency groups, sports, people with non-conforming figures, fashion and entertainment industries, custom clothing manufacturers, and the ready-made clothing industry.

The Air Force, NASA, U.S. Army, and emergency groups need custom fitting for special clothing where flexibility in movement is critical (J. Hoffmeister, personal communication, September 1995). People performing simple gross body movements complain as the ease in the garment decreases (Adams, 1993). Furthermore, wearing personal protective garments, movements were reduced up to 24% when coveralls were undersized instead of oversized (Adams, 1993).

Athletes, too, need clothing that permits freedom of movement to enhance their speed or skill. People buy costly, specialized attire for all sports including horseback riding, hunting, fishing, bicycling, running, exercising, skiing, swimming, motorcycle riding, and tennis. They need clothing that enhances their freedom of movement, and these people are willing to pay more for a good fit. For example, one of the first custom-fitted types of apparel was for snow skiing boots where a comfortable fit was found to be valued above cost (Burns, 1993).

People with non-conforming figures also want up-to-date, fashionable clothing that fits. Unfortunately, "only 25 percent of the garments consumers buy off the rack fit well" (Off, cited by Wright, 1994, p. F3). A person whose figure conforms to the standard garment dimensions is very rare (Murphy, 1995). Shim and Kotsiopulos (1990) believed that the reason for the cause-of-fit problem was that apparel manufacturers and retailers for women's clothing have not recognized the needs of petite and plus-size women.

LaBat (1987) said that 12% of working women are too short, and 20% are too tall for the average industry standards.

Females are not the only ones that do not consistently conform to ready-made garments. Big, tall, and short men are also dissatisfied with the fit and/or the limited selection of clothing (Shim & Kotsiopulos, 1990; Shim, Kotsiopulos, & Knoll, 1990). Moreover, disabled persons need clothing constructed for fit, comfort and adaptive use (Thornton, 1990).

Apparel history shows that fashion silhouettes repeat themselves in recurring cycles (Flugel, 1965; Frings, 1987). "These cycles change approximately every 5-10 years. Unfitted has been the mode, so it is likely the swing will be again to fitted--requiring more custom fit" (C. A. Colburn, personal communication, April, 17, 1996).

In historical interpretation, the theater and entertainment arenas have apparel custom made to enhance assets to emphasize a character's features or to replicate the style and fit of clothing from earlier periods. Hundreds or thousands of hours may go into construction of these costumes, many of which are custom fitted (Tillotson, 1996). Custom-fitted costumes designed for appearance and fit have traditionally used the tape measure tool in the production process, but might benefit from other methods such as digitizers or scanners. For example, a university theater department needed a 15-foot tall character wearing a long cape to move across a stage. The actor stood on a 10-foot rolling platform supported by an extension with a support rod bent to keep the actor secure. The metal support circling the waist had to conform to the actor's body to hold the actor securely while still allowing the actor to perform while the platform was moving. The waistline circumference support might have been more easily constructed to the appropriate curvatures had a three-dimensional scanner and digitizer been available (C. A. Colburn, personal communication, October 19, 1995).

It was predicted that "by the end of the decade, clothing retailers may be able to visit a manufacturer, sit down at a computer, order the style, color and number of shirts or dresses they want, and have the order delivered in hours instead of weeks" (Wright, 1994, p. F3). A glimpse of the future occurred in a trade show in 1995, when Off guided people (attendees at the show and shoppers in Michigan) to select and order a shirt. Then Off, with the help of consortium members, computer sized, printed, cut, sewed, and delivered the shirt to the shopper in four to six hours. Off predicted that a retailer could redesign a garment with a fashion designer in New York, and with agile manufacturing have the garments delivered in less than five days. Off's opinion is supported by Stern who patented stitchless garments in 1981 ("Stitchless garments," 1986). Stern predicted that someday a customer could walk into a store, be scanned, and walk out with an affordable custom garment.

Another scenario of custom-made clothing is that "shoppers will be able to walk into a computerized booth at a mall, have their body size scanned, and get a custom-made shirt in as few as three days" (Wright, 1994, p. F3). Apparel designers and others are envisioning "body scan technology that could solve the problem of sizing" (Off, cited by Wright, 1994, p. F3). However, these people recognize that "technology such as the body scan is still being perfected and could become widely available in about five years" (Off, cited by Wright, 1994, p. F3).

This scenario may come to be a reality, as funding is being provided to improve technology in the textile/apparel industry for manufacturers in the United States. The textile/apparel industry is the second largest industry in the United States and can benefit from improved technology (Off, 1995). In 1993, sport clothing sales were $10 billion and sport shoe sales $6.2 billion (U.S. Department of Commerce, 1994, no. 407). The Department of Energy funded $25,000,000 for research in "dynamic process controls, material characterization and standards, 3-D sewing and alternative joining methods, and 'chameleon' thread" (Hasty, 1994, p. 66). A utility company signed a $500,000 contract, and the Department of Health and Human Services awarded a $500,000 grant to a consultant, McAfee, for manufacturing custom uniforms (Nett, 1995).

Interest in three-dimensional scanners appears to be accelerating. In September 1995, the first full body scanner (at a cost of more than $400,000) was delivered to an Air Force base. At the same time, three other full body scanners were being processed for the U.S. Army, NASA, and an organization for the disabled. As prices fall, the technology will be more widely available, and studies will help in determining the benefits of using a three-dimensional measurement device for measuring bodies to provide data to produce clothes that fit.

As indicated, there is a great deal of interest in using technology to improve clothing fit. Further research will help ensure informal decision making in this field.

Hypotheses

Two hypotheses were addressed in this study. These hypotheses address the reliability of measuring with the tape measure versus the digitizer, and the reliability of each method for specific body location measurements.

H_1 Data from measurements with the digitizer vary less than data from measurements with a tape-measure at the 0.05 level of significance.

H_2 The data from eight complex surface measurements taken with a digitizer vary less than data from a tape measure at the 0.05 level of significance.

Assumptions

The following assumptions were made in this study:

1. The introductory demonstration gave operators sufficient training to operate the digitizer correctly.

2. A randomized order for the four measurement sessions reduced the intervening variables such as the operator's learning curve.

3. Rotating between centimeters and inches and verbalizing the measurements instead of writing them down reduced the biases caused by recall.

4. The computer aided drafting program and its algorithm calculated circumferences and lengths with acceptable precision.

5. The waistline was the shortest circumference around the middle torso and the hipline had the longest circumference around the lower torso.

6. The external environmental factors (i.e., barometric pressure, humidity, temperature, air movement and surrounding sounds) did not significantly affect this study.

7. The multiple demonstrations (one per half-hour) were equally informative in preparing the operators to use the digitizer, and therefore, did not significantly affect this study.

8. The data recorded in the upward direction, at the beginning and at the end of a series of scans, were due to repositioning of the digitizer and not part of the actual measurement.

Delimitations

The following delimitations were inherent in this study:

1. This study was delimited with respect to time and location. This study was conducted in a business facility, Engineering Animation, Inc. (Appendix A) near Iowa State University. The equipment was available for four hours.

2. The sample operator group were textile and clothing staff, graduate students, retired professors, and their friends and neighbors experienced in sewing who had previous familiarity with measuring human forms and dress forms with a tape measure.

3. The study was delimited to the individual sonic digitizer employed in the study.

Limitations

The following limitations were inherent in this study:

1. The type of digitizer used was dependent upon the kind owned by a company willing to lend it to the researcher.

2. The dress form's surface (muslin over padding) yielded slightly to a firm touch.

3. The metric tape measure's millimeter units were smaller than the inch tape measure's sixteenth inch units.

4. Operators appeared less comfortable with metric tape measurements than with inch tape measurements.

5. The edited extraneous points were limited to those at the ends of the line sweeps. What appeared as loops, hesitations, pricks, and crossover lines were not edited.

6. Changes in technology and the variety of computer programs available may affect replication of this study.

Operational Definitions

The following terms were used in this study:

Agile manufacturing: The process of manufacturers adapting to constant and unpredictable change (Gardner cited by Ghering, 1996).

ANSI: American National Standard Institute's used here as standards for computer interface.

ASCII: American Standard Code for Information Interchange. In this paper, the three-dimensional coordinates were saved in ASCII format as comma separated variables (X dimensions, Y dimensions, Z dimensions listed in columns).

CADD: Computer-aided drafting and design.

Center back: The vertical distance from the base of the neck (at the neckbone) to the waistline along the back (all dimensions were in inches or centimeters).

Center front: The vertical distance from the hollow between the collarbones and the waistline front (Margolis, 1959).

Circumference: The distance "in a single plane around a body segment or area" such as the waist circumference (Roebuck, Kroemer, & Thomson, 1975, p. 15).

Digitizer: In this study, digitizer refers to a three-dimensional digitizer (see three-dimensional digitizer below).

Dress form: A model duplicating the shape of a human figure used for draping or fitting or modeling clothes. Also called model form or figure (Kopp, Rolfo, Zelin, & Gross, 1984). Dress forms are updated to government standards (Amaden-Crawford, 1989).

Ease: The difference in the garment dimension and the human body dimension; the extra fabric added to give room for flexibility and movement (Oblander, Ekern, & Zieman, 1978).

Frontal plane: A principal plane in the human body between the front and the back (Roebuck et al., 1975).

Hipline: The largest circumference around the hips (Thornton, 1990).

Hipline depth: The vertical distance from the waistline to the hipline at center front, center back, left side, and right side.

IGES: Initial Graphics Exchange Specification published by the U.S. National Institute of Standards and Technology (Latham, 1995).

Microphone: An electro-acoustic transducer that responds to sound waves and delivers essentially equivalent electric waves (American National Standard Acoustical Technology, cited by Peterson, 1980).

Probe: In this report, a probe was a stylus or tool in the shape of a gun, but with a point resembling a knitting needle protruding from the barrel. When the trigger-like switch was pulled, two ultrasonic sound spark emitters snapped. By triangulation mathematical calculation, the distance to an object from the pointed tip of the knitting-needle-like barrel coordinate was recorded.

Reliability: The probability that the measuring tools will determine dimensions after a period of usage (Morris, 1992).

Reverse engineering: Duplicating an object such as an industrial model, an old machine part, or a work of art (Burns, 1993).

Sagittal plane: A principal plane in the human body between the left and right (Roebuck et al., 1975).

Sound: An oscillation in pressure, stress, particle displacement, particle velocity, etc., in a medium with internal forces, or the super position of such propagated alterations (American National Standard Acoustical Technology, cited by Peterson, 1980).

Surface: Three or more (X,Y,Z) coordinates (point, line, grids, or triangulation) defining a plane or curved area representing a surface or solid.

Three-dimensional scanner: A device that optically senses and records the (X,Y,Z) coordinates of a recognized unit.

Three-dimensional digitizer: A device usually consisting of a probe and receptor to record X, Y, and Z coordinates into a usable format, i.e., DXF, IGES, ASCII. The X,Y,Z coordinates were converted into points, lines, grids, triangulations, etc. to form a shape.

Ultrasonic waves: Sound waves above the audible frequencies (Kleppe, 1989). The SAC ultrasonic digitizer detects a broad range of frequencies from 20 to 100 kHz.

Waistline: The smallest portion of the torso.

CHAPTER II

REVIEW OF LITERATURE

The review of literature covers seven areas: (a) apparel, (b) three-dimensional scanners and digitizers, (c) sound influences, and (d) variation in measurements, (e) human body measurements, and (f) summary.

Apparel

The textile and apparel industry is the sixth largest industry in the United States and accounts for 8% of the manufacturing jobs (Off, 1995). Despite its size and dominance, "many [textile/apparel] companies have succumbed to import competition" (Finnie, 1995, p. 7). This competition from imports has grown significantly and represents over 50% of the apparel consumption (Off, 1995). Import trade in 1994 was $9,209,000,000 for textiles and $38,444,000,000 for apparel. On the other hand, these imports compared with exports of $6,429,000,000 for textiles and $5,595,000,000 for apparel, and the import/export imbalance is increasing (Finnie, 1995). Efforts to make the United States textile/apparel industry competitive in the global market stress differentiation, innovation, flexibility, partnerships, communications, and focus.

In the innovation arena, "body scan technology could solve the problem of sizing . . . and could become widely available in about five years" (Off, cited by Wright, 1994, p. F3). Knight and Cassill (1994) predicted consumers will get a three-dimensional body scan in a special dressing room booth where they will wear body suits or undergarments.

Measurements would be completed in six seconds and the data stored in the computer system and/or on a data card. Wright (1994) predicted retailers will order garments, specifying color, quantity, and style via a computer and have the garments delivered within hours instead of weeks. In addition, Stern ("Stitchless garments," 1986) envisioned the future with a patented process for manufacturing garments without seams.

In order to be competitive, the textile and apparel industry needs to move to custom fitted clothing. One reason for change is that finding people who can fit "standard" dimensions is rare (Murphy, 1995). In a survey, Knight & Cassill (1994) learned that over half of the women had to alter the clothing they had purchased. Off (cited by Wright, 1994) explained that 75% of the garments sold off the rack do not fit. Twelve percent of working women are too short and 20% are too tall (LaBat, 1987). "Forty-five percent of all women in America wear a size 14 or larger and the baby boomers are getting older, and they're getting bigger" (Fritz, cited by Gustin, 1996, p. E1). The clothing selection is meager even for big, tall and short men (Shim & Kotsiopulos, 1990; Shim et al., 1990).

Yet another reason industry should move to custom fitted clothing is when one looks at clothing size, "there is no industry-wide size standard" (Wolf, cited by Brotman, 1996, p. E3). An old pair of 9/10 Gap jeans fit the same as with a new size 6 Gap jeans, Banana Republic size 4 new, or Linda Allard/Ellen Tracy size 2 (Brotman, 1996). Delk and Cassill (1989) studied the fit of thirty jeans (ten brands, three sizes) matching the size range to a model's measurements. Two jeans were acceptable, while twenty-eight did not fit. "A size 8 may have a waist measurement of 29½, but a size 10 of the same brand may have a 28½ waist . . . if the jeans do not fit, they will not be purchased" (Delk & Cassill, 89, p. 20). The "female is busier than ever . . . she is not going to give up her leisure time to go through 28 pairs of jeans, just to find two pairs to choose from" (Delk & Cassill., 1989, p. 20). Staples et al. (1994) predicted that three-dimensional scanning will help retailers "assist customers in selecting a best-fit size" (p. 48).

A proper fit when wearing clothing contributes to comfort and freedom in movement (Adams, 1993). This comfort and freedom in movement means a garment can be worn for a longer period of time (J. Hoffmeister, personal communication, September 1995). Most dissatisfaction with garments relates to poor fit including pants, outerwear, skirts, suits, and dresses (Chowdhary & Beale, 1988). In addition, there is dissatisfaction with size of garments including suits, outerware, skirts, pants and dresses. Dissatisfaction might well be related to size 14 and larger garments. Garments are designed for a standard size 10. Garments made in other sizes became more and more distorted when graded via the computer-point approximation technique which is based on the size 10 (Karlsson, 1986). Comfort and freedom relate to fit and it has been stated, "Fit plays a critical role in purchase selection: purchasers of apparel are satisfied with fit; non-purchasers are not" (Eckman, cited by Yoon, 1992, p. 13).

Consumers are willing to pay for custom fit clothing. Customers responded favorably to paying $15 more for custom fit Levi jeans (Holusha, 1996). More than half of the women in a survey said "they would be willing to pay more for apparel made to their own size specifications" (Knight & Cassill, 1994, p. 102). A scanned, custom-made garment would be more expensive, but large women, would prefer to buy well fitted garments rather than less expensive discount garments (Chowdhary & Beale, 1988). An acceptable cost of $20 to $40 for alterations is built into the cost of men's suits (Off, cited by Holusha, 1996). Men pay $800 to $1200 for a custom, made-to-fit suit (T. Melody, personal communication, March 9, 1996). Also, considerable money is spent on specialized attire for sports (Burns, 1993). In fact, $10,000,000,000 was spent on sport clothing in 1993 (U.S. Department of Commerce, 1994).

There has been financial assistance for research to update the technology in the textile/apparel industry. In the United States, the government provided $25,000,000 for research in "dynamic process controls; material characterization and standards; three-dimensional sewing and alternative joining methods; and 'chameleon' thread" (Hasty, 1994, p. 66). The House Appropriation Committee allocated $3,000,000 to TC^2, a research and development company for the textile/apparel industry, and $7,000,000 to the National Textile Center (Nannery & Clune, 1995).

Off (1995) predicted a virtual organization with a garment designed in New York, approved in Dallas, and sold in Atlanta or Ann Arbor, Michigan. At a trade show, this garment preparation was demonstrated. Attendees ordered a shirt and received the finished product within four to six hours.

"If manufacturers used the body dimensions of individual customers, the standard sizes which vary from maker to maker anyway, would become obsolete. Along with a custom fit, there would be a premium [placed on the] speedy delivery of garments. This would drive manufacturers to keep their plants in the United States rather than waiting months for goods to arrive from factories in East Asia" (Holusha, 1996, p. D6).

Three-Dimensional Scanning and Digitizing

Digitizers or scanners are used to measure three-dimensional objects and the data files often consist of thousands of data points ("Digitizing with less," 1994). The methods of processing data from three-dimensional scanning and digitizing are by triangulations or by radar analog. Triangulation is "a system consisting of a light [or sound] source . . . , a mechanism to project the light spot [or sound emitting probe] onto the object surface, and a position sensor [microphone]. The distance measurement is calculated by trigonometric algebra applied to the projection direction." Triangulation is a method of calculating a position using a light or sound emitter, sensors, and trigonometric algebra (Rioux, 1984).

Three-dimensional scanners or digitizers are classified by four methods: (a) Rioux (1984) classified three-dimensional scanners and digitizers as active or passive. (b) Wohlers (1992) classified digitizers and scanners by contact and non-contact. (c) A third method to classify these measurement tools is by groups of scanners (plane and line) and groups of digitizers (line and point). (d) A fourth method classifies scanners and digitizers according to the work-engine method: light, photogrammetric, electro-magnetic, sonic, mechanical, and laser-sensing systems. These classifications are listed in Figure 1.

Figure 1. Three-dimensional scanners and digitizers available off-the-shelf were surveyed for work engine, uses, file format, platform, envelope, accuracy, size, weight and price (four pages).

Scanner/Digitizer (Manufacturer)	Uses	File format/Platform	Envelope Accuracy	Size dimensions WxHxD Weight	Price
Light (electro-optical) Image Guided Technology (FlashPoint™ 5000)	Capture of models, reverse engineering, inspection, and tracking (instruments i.e. forceps in surgery).	ASCII (X, Y, Z direct from the digitizer) DXF, CDL, IGES (using optional software) DOS, MAC	1 m sphere, expandable with FlashTracker™. .1mm. 360 points per second	Sensor assembly: 45.67" x 2.5" x 3" (1160 mm x 63 mm x 75 mm)	FlashPoint 3000: $18,900 FlashPoint 5000: $24,900 Additional: maximum 128 emitters.
Photogrammetry Geodetic Services, Inc. (STARS film, V-STARS digital)	Reverse engineering, periodic inspection, surface digitization, automotive, aerospace, nuclear, shipbuilding, CAD model design comparison. These systems are meant for very high accuracy measurement tasks of large objects that cannot be brought into a laboratory area.	ASCII (can be converted to DXF, IGES using optional software) STARS: DOS V-STARS: Windows 95, Windows NT	Approximately 6 feet to 500 feet STARS: 1:500,000 (i.e. .0005 inches over a 20 foot object) V-STARS: 1:100,000 (i.e. .0025 inches over a 20 foot object)	STARS Monocomparator: 42" x 36" x 36", 350 lbs. STARS Camera: 12" x 12" x 12", 45 lbs. V-STARS Notebook computer, 7 lbs. V-STARS Digital camera: 7" x 6" x 6", 8lbs.	STARS: $235,000 V-STARS: $125,000
Imetric 3D Image Metrology SA. (TP 210, TP 610, TP 252, TP 254, TP 262)	Aerospace and automotive industries, measurement, quality control, construction, stability testing.	ASCII, IGES, VDA/FS, ECDS DOS, UNIX	12mm to 20m 1536x1024 or 3060x2036 pixels (i.e. .02mm for a 2 m object, .1mm for a 10m object)	Camera: 7" x 5" x 10" (can use up to six cameras), 5 lbs. TP 210 and TP 610 include a SPARK notebook: 8" x 12" x 2", 5 lbs. TP 252, TP 254, TP 262 workstation: 40" x 20" x 25", 40 lbs.	$100,000 to $300,000

(figure continues)

Scanner/Digitizer (Manufacturer)	Uses	File format/Platform	Envelope Accuracy	Size dimensions WxHxD Weight	Price
Electro-Magnetic Polhemus (Figure 2)	Medical tracking of motion during surgery, medical simulation, digitizing museum artifacts, analysis of skulls and bones, graphics	To date, this is a stand alone unit, the Mira company specializes in software to translate the data to other formats. CDL, DXF, ASCII	0 to 30 to 120 inches (76 to 305 cm) .006 to .0002 inch/inch range with accuracy .25 to .03 in. RMS. Environment sensitive.	Electronics unit: 279x290x91 mm Power supply: 178x94x56 mm Transmitter: 53x53x54 mm Receiver: 23x28x15 mm Electronics unit: 1.8 kg Power supply: 0.6 kg Transmitter: .26 kg Receiver: .02 kg	$3,175 to $6,500 (includes system electronics unit, power supply, transmitter, receiver) RS-422 $100; Additional receiver $500, transmitter $500; Stylus $800;
Sonic SAC: Science Accessories Corporation (Freepoint 3D XL-1, Freepoint 3D XL-2, Freepoint 3D XL-D diamond) (Figure 3)	Reverse engineering, rapid prototyping, design, modeling, measuring, inspection: automotive, aerospace, marine, utilities, defense, manufacturing, apparel, packaging, graphics, animation, entertainment, construction, research, medical markets.	ASCII PC DOS, windows, drivers for MAC, and Amiga	Freepoint 3D XL-1: 3.25' x 3.25' x 3.25' (1 meter cube) Freepoint 3D XL-2: 8' x 8' x 8' (2.24 meter cube) Freepoint 3D XL-D: 16' x 8' x 8' (4.8 x 2.4 x 2.4 m) 0.002 inch (0.005 cm)	Control unit and multiplexer 17.3 x 3 x 3.15 in. (37x18.6x25 cm) Sonic digitizer emitter 1/2x1/8": 11.5 lb (5-6.35 kg)	Freepoint 3D XL-1: $4995 Freepoint 3D XL-2: $5965 Freepoint 3D XL--D: $6995 (all above include probe, triangular or diamond detector, cabling, power supply, DOS TSR interface software) Control rod, third party software for DXF, DWG, IGES, OBJ
Mechanical FARO Technologies, Inc. (FaroArm, Metrecom, Surgicom, SpaceArm) (See Figure 4.)	Industrial inspection of parts, 5-axis programming, reverse engineering, 3D modeling; medical musculo-skeletal measurements, range of motion, scoliosis screening; surgical locator/guidance tool for neurosurgery; animation, graphics modeling	.DWG .DXF, IGES, ASCII, DES, MOD, VDA, CSF, RS232-ACL 494A 486 PC or MAC	4 ft. and up to 12 ft. (to 3.7m) sphere diameter ±.003 to ±.016 inch (0.1mm to 0.4mm) (ansi B89)	10 to 35 pounds (4 to 16 kg)	$2,295 to $76,400 (industrial units include six axis arm, RS232 controller box, 3 probes, mount plates or clamp, Caliper 3D software, one day training).

(figure continues)

Scanner/Digitizer (Manufacturer)	Uses	File format/Platform	Envelope Accuracy	Size dimensions WxHxD Weight	Price
Immersion MicroScribe-3D™, MicroScribe-3DXL, MicroScribe-3DL	graphics, animation, design, industrial inspection, medical, neurosurgery	.DXF .OBI .IGES .DWG .TXT DOS, Windows 95, MAC, UNIX	MicroScribe-3D: 50" sphere ±0.015 (ansi B89) MicroScribe-3DX: 50" sphere ±0.009 (ansi B89) MicroScribe-3DL: 66" sphere ±0.019 (ansi B89) resolution: 0.001	6 x 6 x 16 inches MicroScribe-3D: 7 lbs MicroScribe-3DX: 7 lbs MicroScribe-3DL: 7 lbs	MicroScribe-3D™ $2995 MicroScribe-3DX™ $3995 MicroScribe-3DL™ $4995 Includes digitizer, power adapter, Vortex-3D software for DOS, Hyperspace for Windows and MAC, Inscribe for Windows 95, Windows NT, and UNIX. Accessories: foot pedal; rotary table
Romer Inc. (Romer™ ModelS61000, Model S6-2000, Model S6-2200, Model S6-2500, Model S6-3000; ELVIS-extendable large volumetric inspection system, HOMER-portable ELVIS)	automotive: engine compartments, driver compartment, underneath the automobile; electric turbine inspection for corrosion or wear; inspection of air conditioner and cooling unit main frame and subassembly frame on tractor trailer trucks; reverse engineering.	DMIS, IGES, ASCII [portable Pentium PC comes with the digitizer]	Romer Model 1000: 9.0' sphere Romer Model 2000: 6.5' sphere Romer Model 2200: 7.8' sphere Romer Model 2500: 9.0' sphere Romer Model 3000: 10.0' sphere ELVIS: A laser positioning system extends sensor arms to a 20 x 20 foot area. ±.002 to ±.005 inch (ansi B89)	Romer Model 1000: 14 lbs Romer Model 2000: 19 lbs Romer Model 2200: 24 lbs Romer Model 2500: 28 lbs Romer Model 3000: 35 lbs HOMER: less than 50 lbs Transportable in two standard suitcases.	Starts $55,000 (six axis arm, 3 probes, Surastuff software, Pentium notebook computer, printer) Accessories: DMIS software, contact and non-contact probes. Non-contact probes include an infrared (for inspecting inside pipes and ducts), laser (so not to touch or mar surfaces, to measure soft surfaces), and theodolites.
Laser Cyberware (Figure 5)	Bust (head) sculpting, reverse engineering, full body scanning, in XYZ coordinates and RGB color in 17 seconds.	IRIS, IGES, OBJ, Alias, DXF, Wavefront, NC Tools Paths, ASCII, Softimage, OBJ Silicon graphics workstation	Scans objects or portions of objects 12"x12"x12" .4mm 15,000 points per second 3030 RGB	506x281x376 mm not including platform 22-23 Kg	$53,000 to $410,000 (includes optical unit, power supply, interface, cabling, documentation, software, installation and training, travel expenses, one year warranty and support) Motion platforms $7,000 to 23,000

(figure continues)

Scanner/Digitizer (Manufacturer)	Uses	File format/Platform	Envelope Accuracy	Size dimensions WxHxD Weight	Price
Laser Design (Surveyor 500, Surveyor 2500, Surveyor 3500, Surveyor 5000, Retrofit)	Reverse engineering, duplication, inspection, quality assurance, rapid prototyping in automotive, aerospace, medical, sporting goods, bottle-making, military	IGES, ASCII, .IBL, NC toolpaths, HPGL, .WAV	Surveyor 500: 12" x 6" x 6" Surveyor 2500: 25" x 16" x 20" Surveyor 3500: 30" x 30" x 24" Surveyor 5000: 5' x 8' x 4' Sensor accuracy: Line range sensor: .0005"/.013mm Point range sensor: .0004"/.01mm 2,000 points per second	Retrofit 7" diameter x 7" high (without platform) Including platform: 27x30x40" to 12x21x14' 3.2 Kg (laser head only) (159-1590 Kg includes platform)	Surveyor 500: $74,000 Surveyor 2500: $143,000 Surveyor 3500 $198,000 Surveyor 5000 $400,000 Retrofit (laser head) $40,000 all with DataSculpt® software.
Perceptron (Lasar)	lumber industry, unmanned vehicle navigation, robot bin scanning and picking, robot guidance, inspection, validation, pothole repair	Windows and UNIX	up to 10 to 20 m^3, 45° x 45° angle, ambiguity of interval 1.87, 9.37, 15, 37.5 meters .1 to .5 inch, 147,000 to 187,000 to 36,000 points per second	Camera head: 140x210x210 mm 7.7 Kg	$50,000
3D Scanners Ltd.	Reverse engineering and copying, jewelry, cutlery, full body scans	NC Tool paths, ASCII, STL, IBL, DXF Alias, Wavefront, Softimage	.001mm x .001mm to 1000mm x 1000mm x 475mm	Head: 600 gm Machine: to 500 Kg	$25,000 - $100,000
Spacial MetriX Corporation (CMS-3000)	Large scale analysis to build, inspect, layout for turbine airframe, antenna, shipbuilding, robotic and automotive applications.	Windows XTSI 486 or higher	100 foot cube 2.0 Microns/M	15.8 x 23 x 10.6 inches Head 79 pounds Power unit 25 pounds	$131,000
Spatial Positioning Systems, Inc. (Odyssey)	Rapid prototyping, modeling, inspection, quality control, motion tracking. Industries: construction, shipbuilding, automotive, aerospace, animation, research and defense	ASCII (X,Y,Z, description-1, description-2) DOS	1m x 1m x 1m to 100m x 100m x 50m 0.5mm	Sensor/wand: 4cm-Dia x 75cm Data collector: 5.5cm x 13 cm x 1 cm Transmitter (2 required): 18cm x 21cm x 50cm (11 kg)	$98,500

(figure continues)

Scanner/Digitizer (Manufacturer)	Uses	File format/Platform	Envelope Accuracy	Size dimensions WxHxD Weight	Price
Digi-botics (Digi-bot II)	Reverse engineering, inspection, animation for video games, hearing aides, anthropological artifacts, objects for packaging form and design.	ASCII, IGES, DXF, VDA, OBJ, IBJ, STL PC, windows	18" diameter x 18" high cylinder .002 inch (1 sigma)	44x28x30 inches 110 pounds	$49,500
Hymarc (Hyscan "flying spot")	Retrofits to any CMM. Automotive inspection and design; rapid prototyping; reverse engineering in toy, sport equipment (i.e. helmet, shoes), medical prosthetics.	ASCII, IGES, DXF, Silicon Graphics, PC	Model 25: 70 x 40 mm Model 80: 80 x 80 mm both models: standoff 100mm Model 25: ±0.001 inch (.025mm) (3 sigma) Model 80: ±0.002 inch (.005mm) (3 sigma) up to 10,000 points per second	260x112x86 mm 2.2 kg	$35,000 to $75,000 (includes optical unit, power supply, interface, cabling, documentation, software, installation and training, one year warranty and support)
Sharnoa Corporation (Xtrolaser)	Digitizing and CNC machining package. Reverse prototyping, mold making, engraving, dye stamping for: automotive, aerospace, jewelry, toys.	ASCII, IGES (106, 112) .VDA .STL, .DXF G-Code PC-DOS	0 to 30 or 85 inches ±0.0004 inch	Laser 6x6x3", or with shroud approx. 7x7x5". 6 to 8.5 pound probe Optional platform 22,000 to 43,000 pounds	$39,000 to $65,000 laser system only.

Examples of four work-engines viewed at SIGGRAPH (Appendix A), a graphics trade show, were demonstrated to the author in Figures 2, 3, 4, and 5. An electro-magnetic digitizer (Figure 2), by Polhemus (Appendix A), was used to measure a one-half-size dress form. This electro-magnetic digitizer recorded the magnetic location of a probe on an object placed on a stand/shelf for digitizing while the detector was below the surface. A sonic digitizer (Figure 3), by Science Accessories Corporation (Appendix A), traced the same dress form. It had a "gun-shaped" probe with two sound emitters. To digitize, the probe was activated, the microphones recorded the emitted sound waves, and the control unit calculated the time interval over which the sound traveled. A pilot control assembly (a sound emitter and microphone a known distance apart) compensated for environmental changes (temperature, humidity, and atmospheric pressure) that affected the speed of sound. A mechanical digitizer (Figure 4), by FARO (Appendix A), was used to demonstrate the measurement of a one-half-size dress form. This digitizer, sometimes called a portable, coordinate, measuring machine, resembled a robotic arm that operated in reverse, where the arm was positioned and the probe tip location recorded. A laser scanner (Figure 5), by Cyberware (Appendix A), scanned the one-half-size dress form, and a vertical laser line was emitted for measuring distances along the surface. Two white bulbs shown in the figure were used to aid in recording color.

Research is in progress to digitize/scan the human body for measurements for custom fit clothing. Three body-scanner manufacturers involved with these measurements were listed by Staples et al., (1994) and included: Cyberware, Laser Design, and

Figure 2. An electro-magnetic digitizer by Polhemus is used to measure a one-half-size dress form at SIGGRAPH.

Figure 2. An electro-magnetic digitizer by Polhemus is used to measure a one-half-size dress form at SIGGRAPH.

Figure 3. A sonic digitizer by Science Accessories Corporation is used to measure a one-half-size dress form at SIGGRAPH. Note the triangular microphone frame on the wall.

Figure 3. A sonic digitizer by Science Accessories Corporation is used to measure a one-half-size dress form at SIGGRAPH. Note the triangular microphone frame on the wall.

Figure 4. A mechanical digitizer by FARO is used to measure a one-half-size dress form at SIGGRAPH.

Figure 4. A mechanical digitizer by FARO is used to measure a one-half-size dress form at SIGGRAPH.

Figure 5. A laser scanner by Cyberware is used to measure a one-half-size dress form at SIGGRAPH. In the top two photos, the scanner circled around the dress form. In the bottom photo, the data, wireframe, and color surface is viewed in the computer monitor.

Figure 5. A laser scanner by Cyberware is used to measure a one-half-size dress form at SIGGRAPH. In the top two photos, the scanner circled around the dress form. In the bottom photo, the data, wireframe, and color surface is viewed in the computer monitor.

Textile/Clothing Technology Corporation (TC^2). The United States Air Force was actually the first group to purchase a full body scanner by Cyberware for measurements (J. Hoffmeister, personal communication, September 1995). Cyberware and Laser Design are also listed in Figure 1. The group TC^2 is an organization for research and development, and they utilize six video cameras while scanning a person (Off, 1995). A fourth company that depicted three-dimensional body scanning in a brochure was called 3D Scanners Ltd.

Raw data files need editing. "A great deal of work typically must be done . . . to reduce or 'sweeten' the data before it assumes a form that can be fruitfully manipulated by a CAD/CAM system" ("Digitizing with less," 1994, p. 154). For example, with a three-dimensional body scan, "the resulting line looks a bit lumpy at first, but after smoothing, the line simulates the equivalent of a tape measure being placed on the body" (Staples et al., 1994, p. 50).

Environmental Influences on Sound

The sonic digitizer, by Science Accessories Corporation (SAC), was the instrument selected for this study. To understand potential problems when operating a sonic digitizer, environmental influences must be understood. Sound is influenced by the sound wave path, temperature, humidity, atmospheric pressure, wind, and refraction.

Sound Wave Path

One concern when using the three-dimensional digitizer is to maintain a clear path between the sound emitters and the microphones (Science Accessories Corporation, 1994). Sound waves travel in a spherical pattern away from the source. When sound waves encounter an object, the direction of travel is impeded, and the sound waves are reflected (Harris & Cyril, 1991). If measurements are made near a sound source (emitters), it is advisable for the observer to stand well to the side of the direct path between the source and the microphone. Peterson (1980) emphasized that operators should avoid interfering with the sound path, and they should not stand between the microphone and sound source when taking measurements.

Temperature

As the temperature rises, the speed of sound increases. The formula is $C = 331.6 + 0.6T$ where C represents the sound in meters per second and T represents temperature in degrees Celsius (Kinsler & Frey, 1962). Microphones should be adjusted if they are used in environments with temperatures other than normal room temperature (Peterson, 1980). Normal room temperature, standardized in industry by ISO and ANSI B89.6.2, is 68°F (20°C) (Blaedel & Parsons, 1993). There is discussion that "normal" may be changed to a more comfortable environment of 73.4°F (23°C) (Blaedel & Parsons, 1993).

Humidity

The speed of sound increases as the relative humidity increases. As humidity and temperature change, amplitude (loudness or power measured in decibels, dB) changes (Harris & Cyril, 1991). Decibels increase between 5% and 25% humidity, peak and then decrease to form a one-sided, bell-shaped curve.

Microphones deteriorate when exposed to high humidity. Precautions should be taken to avoid condensation on microphones in storage and when they are exposed to changes in temperature. This is important especially when a cold microphone is set up in a hot/humid space (Peterson, 1980).

Atmospheric Pressure and Wind

Sound measurement variations due to changes in atmospheric pressure are small (Peterson, 1980). However, the influence of air pressure on acoustics is greater than that caused by humidity (Putland, 1994). Refraction of sound in the out-of-doors changes with temperature and wind speed. According to Hemond (1983), sound waves bend as the atmospheric temperature changes from the source. As the temperature decreases, sound waves bend upward, and a drop off in sound intensity occurs at ground level. As a temperature inversion occurs (as in the evening), sound waves bend down, and skip over an area, causing distant sounds, those from 10 to 15 miles away, to seem close. Air movement or wind bends the sound wave and/or carries the sound wave in the windward direction (Hemond, 1983). High-speed winds affect measurements with microphones unless a foam wind-screen cover is used (Peterson, 1980). Atmospheric pressure and wind can affect the sonic digitizer precision when used outdoors.

Reflection of Sound

When sound waves meet an object (e.g., a wall), the direction of travel changes or is reflected (Harris & Cyril, 1991). Sound will continue to be reflected until it finally dies away (Porges, 1977). Furthermore, measuring instruments and observers should not be too near to the point where sound is measured (Peterson, 1980). Microphones should not be pointed at a hard surface from which sound waves can bounce back and be recorded (Peterson, 1980). "Unless the measurement room is well treated, an appreciable standing wave can exist" from the walls, ceiling, or floors (Peterson, 1980, p. 183). Nearby objects such as furniture, chairs, and equipment create similar problems. Connecting cables can also interfere with microphone measurements (Peterson, 1980, p. 184). Problems with microphones are alleviated by: (a) using rubber pads to dampen vibration, (b) removing electrical instruments that can interfere with microphone measurements, and (c) "putting in deadening sound barriers between instruments and the sound source" (Peterson, 1980, p. 184).

Variation in Measurement

Measurement variations, in general, are defined by repeatability, reproducibility and reliability (Marsh, 1995). Repeatability is the "amount of random error inherent within the measurement equipment" (Marsh, 1995, p. 31). The two pieces of equipment or tools used in this study were the tape measure and the sonic digitizer. Tape measure repeatability is dependent on the original correctness of the tape measure, the resolution of the graduation lines, the tautness of the tape measure, and the angle of direction from which the graduations are read (Farago & Curtis, 1994). The common tape measure graduations are 1/8th, 1/16th, 1/32nd, 1/64th and 1/50th inch divisions. The smallest division is 1/100th inch. For human body measurement, tape measures should be made of steel or plastic, but not linen (Weiner & Lourie, 1969). Another variation in measurement reported by Bader (1991) was that the sonic digitizer readings are within 0.004 inches (0.1 mm) with a distance of 127 cm between the probe and the microphones. Repeatability with the sonic digitizer can be affected by temperature, humidity, and air movement.

Reproducibility is the assessment of the stability among two or more operators (Marsh, 1995). Williams (1982) reported human accuracy when using a stylus to digitize is within 0.005 inches. Wohlers (1992) stated that although companies claim digitizers or scanners have an accuracy of +/- 0.010 inches, the idea of this being true for complex-shaped objects is unlikely.

Reliability is the probability that the measuring tools will determine unchanging dimensions after a period of usage (Morris, 1992). As more tools become computer-controlled, variability even among operators will gradually be eliminated (Marsh, 1995).

Human Body Measurements

Human body measurement accuracy or standardization is addressed by the International Organization for Standardization (ISO) (Yoon, 1992). Bust girth, hip girth and height were the key dimensions graphically defined in a pictogram. Measuring the human body is not always done in a uniform manner. "If more than one anthropometrist is assigned to a study, it is essential that the measurers involved should regularly check the repeatability of their measurements, one against the other" (Weiner & Lourie, 1969, p. 4). It is best to average several measurement readings for accurate results (Roebuck et al., 1975). "Even among anthropologists who are taught the most scientific method of measuring bodies, there is variation in the placement of measuring devices" (Staples et al., 1994, p. 55). Sheldon (1963) reported the waistline to hipline depth varies: the widest hipline levels "are usually found over the trochanters [hip], but in high endomorphy [round build, short legs], they are frequently above the iliac crests [upper pelvic bone], and in high mesomorphy [average frame, muscular] they are often well below the trochanters as is much more frequently the case with women" (p. 57). Green (1981) studied anthropometric dimensions to identify key measurements (hipline circumference, crotch height, bust circumference, center front, and shoulder breadth) to be predictors for size.

Yoon (1992) found variations in human body measurements between measurements recorded by a researcher and measurements recorded by various subjects. After the subjects measured their own body and the body of a partner, the measurements were compared to measurements determined by the researcher. Yoon concluded the hipline circumferences were under-measured an average -4.54 cm; waist breadths were over-measured 6+ cm; and waistline circumferences were consistent. The discrepancies were attributed to variations in pressure applied, different thicknesses of fatty tissue, varying abilities to manage the measuring instrument (subjects did not measure with 1/16-inch precision, but rather with 1/8 or 1/4 inch or larger precision), the investigator's experience and training, instrument resolution, and difficulty in finding body landmarks.

Summary

The textile/apparel industry is the second largest U.S. industry with 9% of the manufacturing jobs. Recent 1994 imports were over 9 and 38 billion dollars for textiles and apparel, respectively. These imports seriously impact U.S. manufacturing. The body-scan technology utilizing digitizers and scanners could return more business to the U.S. textile and apparel industry. This is because custom-fitted garments are very desirable and could be made quickly by means of body scanning. Few people fit well into standard clothing sold today, and with custom apparel, people are willing to pay more for a good fit which allows for comfort and freedom of movement. Together with a custom fit and a premium on speedy delivery of garments, manufacturers might be better able to keep facilities in the U.S.

Three-dimensional digitizers and scanners may be classified according to work-engine method: light, photogrammetric, electro-magnetic, sonic, mechanical, and laser. With a sonic digitizer, triangulations of distance to sound emitters identify the position of the digitizer. A pilot control assembly adjusts for the environmental parameters that affect the sound. Odd input points occur and smoothing of the data is somewhat subjective but necessary to provide practical output. Reliability of measurement incorporates the factors of tool and operator to attain repeatable and reproducible measurements. Measurements of the human body have been shown to be variable. Several measurements of defined areas need to be taken, averaged, and if more than one operator is measuring, the measurements need to be compared between operators. For example, hipline circumference varies by location of measurement, by body type, and by individuals measuring.

CHAPTER III

METHODOLOGY

Methodology addresses research variables, materials, the survey instrument, operators, procedure, ASCII data files of complex three-dimensional object measurements, and statistical methods.

Variables

The types of variables in measuring a complex, three-dimensional object were: constant, independent, modifying, and dependent. The constant variables included the complex, three-dimensional object (a one-half-size dress form) and the setting (room, stand, etc.). Independent variables included the sonic digitizer, tape measures (inch and metric), operators, and locations on the complex object or dress form (waistline, hipline, left hipline depth, back hipline depth, right hipline depth, front hipline depth, center front, and center back). The modifying variable was the randomization of the replications within each treatment. This randomization reduced the impact of the intervening variables, including the operator's learning curve and the time factor. The dependent variables were the data points collected from the digitizer and the measurement lengths obtained by using the tape measures.

Materials

The materials used to determine the reliability of measurements of a complex, three-dimensional object with a digitizer and tape measure were: (a) a one-half-size dress form, (b) a three-dimensional digitizer, (c) tape measures, (d) string, (e) computer, (f) a QBasic program, and (g) a computer-aided design drafting program.

A one-half-size number 12 dress form was used as the complex three-dimensional object (Figure 6), which was a constant variable. It was selected because body-torso shape is not simple geometry (cylinder, rectangle, etc.), it was small enough so that the two sound emitters of the digitizer could be in a direct path to the microphones, and it was a shape where measurement results have potential use in industry. The dress form was manufactured by Superior Model Forms Corporation (Appendix A). The model year of this size 12 dress form is noted to be 1986. This is significant because the shapes or measurements of the dress form are changed yearly according to changes in the population and in styles of dress (Murphy, 1995).

A three-dimensional sonic digitizer by Science Accessories Corporation (Appendix A) was used to record X,Y,Z surface coordinates of the complex, three-dimensional object. The digitizer was owned by a mid-western business, Engineering Animation, Inc. located in Ames, Iowa (Appendix A). The sonic digitizer is a gun-shaped probe consisting of a probe tip, button, and two sound emitters (Figure 7). To begin measuring, the operator placed the probe tip onto the surface of an object, pressed the trigger button, and logged the probe tip's X,Y,Z coordinates. Two spark-gap sound emitters on the probe generated two snap-like clicks that were detected by three microphones. The control unit recorded the sound waves' travel-time intervals and by means of triangulation, calculated the position of the probe's tip derived from the location of the two sound emitters. The

Figure 6. A complex three-dimensional object, a one-half-size dress form by Superior Model Forms Corporation.

Figure 6. A complex three-dimensional object, a one-half-size dress form by Superior Model Forms Corporation.

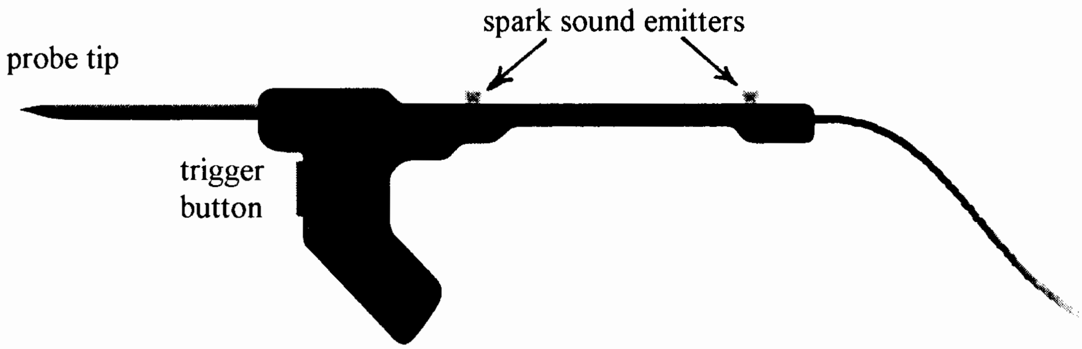


Figure 7. The sonic digitizer probe by Science Accessories Corporation has two spark sound emitters on top of the probe (P. B. Schou, personal drawing, June 1996). To begin measuring, the operator placed the probe tip onto the complex object's surface, pressed the trigger button and moved the probe over the surface of the object. As it moved over the surface, its point location was determined by triangulation of the sound emitted.

Science Accessories Corporation digitizer, (Model GP-12-3D), included a pilot control assembly that, when activated, adjusted for environmental changes involving temperature or humidity. The sonic digitizer was an independent variable.

Other independent variables were two plastic (Weiner & Lourie, 1969) tape measures used in the study, a one-inch tape measure with 1/16 inch graduations and a centimeter tape measure with 1 millimeter graduations. The measurement units were changed to reduce the biases caused by recall when measuring the complex object. The operator tied or pinned the string along the hipline to use as a marker for measuring the hipline depths.

A 486 PC compatible computer, a QBasic program, and a computer-aided-drafting program (CADD) were used to compile and analyze the digitizer's measurements. A QBasic program (Gilpin, 1996) calculated the location of the waistline, hipline, and the perimeters of both. A CADD software program, DesignCAD 3D (1995), generated a complex surface from the multiple ASCII data points, and from it one could get curved line lengths (i.e., the i.e. hipline depths, center front and center back).

Survey Instrument

A custom designed and validated survey for operators was used to record the tape measure data twice (Appendix B): once in inches and once in centimeters. The metric measurements were later computer converted into inches to keep the data in agreement with the digitizer's measurement units. Screening questions on the survey asked the operators the number of years they had been actively sewing, the number of times they had measured a human form with a tape measure, and the number of times they had measured with a digitizer.

Operators

The subjects (operators) were textile and clothing graduate students, staff, retired professors, and home sewers. Operators were chosen based on having experience in measuring the human form. Operators that participated signed the human subject informed consent form (Appendix C) prior to the test. These operators were some of the independent variables.

Procedure

The procedural steps used in the execution of this research were: the setup, demonstration, practice, and measurement of the complex object. Volunteers were on a schedule of two per one-half hour (one every 15 minutes). As some operators completed the measurements, others waited in another area where they could not overhear the verbalized tape measurements.

Setup

The digitizer, microphone, and computer were set up prior to the experiment. Microphone receptors were mounted on a diamond shaped frame and firmly clamped to a tall pole. The digitizer's default mode was set to inch units, pilot control assembly to "on" (to compensate for environmental variables), and continuous log to "on." The complex object was positioned with its right side closest to the wall where the microphones were located. If the object had been set facing the microphone frame, a greater portion of its width would have blocked sound wave paths.

Demonstration and Practice

The operators observed a demonstration on the procedure to use the digitizer. This demonstration included: (a) how to hold the probe while measuring the complex object, (b) where to place the probe's tip when touching a surface (at an angle and not directly perpendicular to an object because the point of the probe could be fragile or poke holes in the fabric covering), and (c) how to turn the probe on and off during the digitizing process. An explanation was provided on how the digitizer worked by sound emitters, microphones, and triangulation. The operators were allowed to hold the probe and turn it on and off during the demonstration.

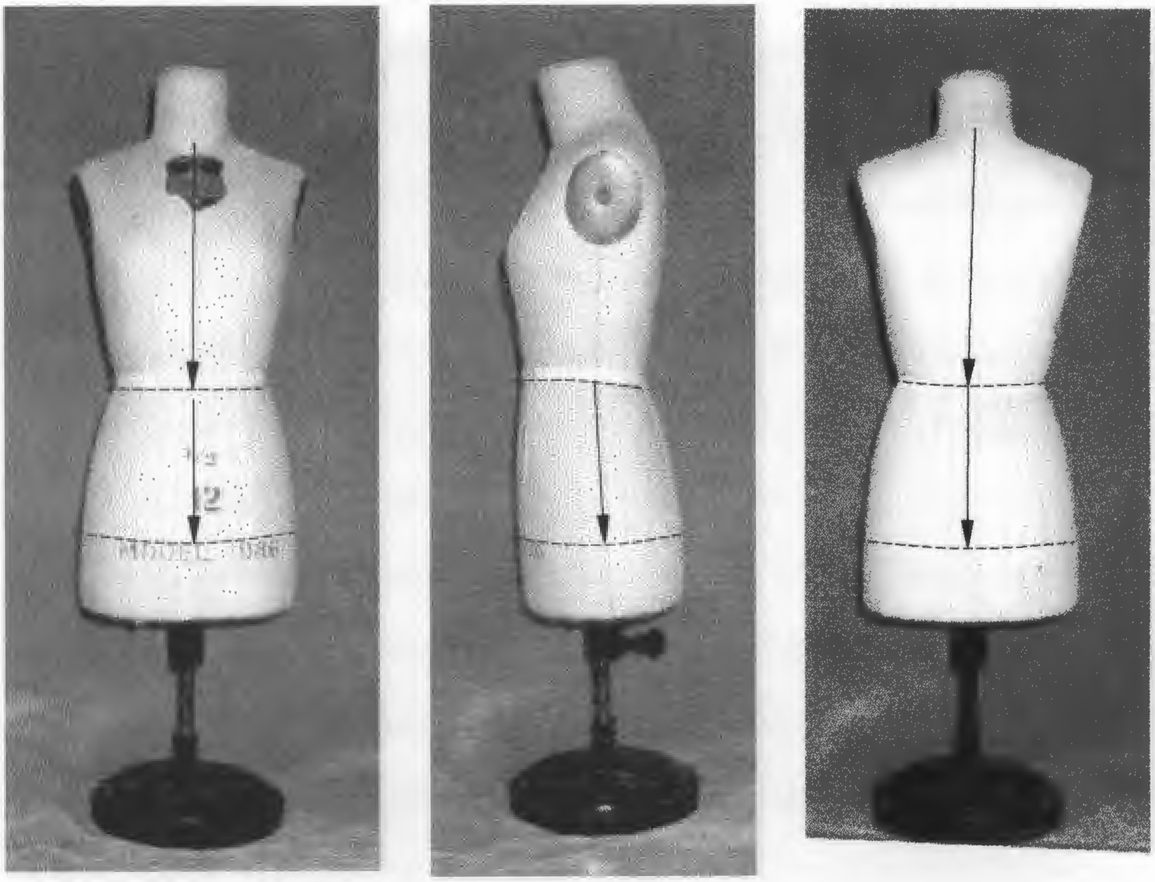
Measurement of a Complex Three-Dimensional Object

Each operator measured the complex three-dimensional object twice with a tape measure and twice with a digitizer. Randomization, a modifying variable, of the four tool measurements reduced the possibility of the influence of sequence, an intervening variable. For example, one operator measured the complex object first with the digitizer (D), second with the tape measure (T), third with the tape measure (T), and fourth with the digitizer (D). Another operator measured the object first with (T), second with (T), third with (D), and fourth with (D). The possible sequences with two replications and two instruments were: DTTD, TDDT, DTDT, TDTD, TTDD, and DDTT.

Measurements critical to this study were waistline, hipline, left hipline depth, back hipline depth, right hipline depth, front hipline depth, center front, and center back. All of these were independent variables. When tape measuring, the operator subjectively located the hipline and tied or pinned a string onto the dress form object, marking this location for the tape measurement of the hipline and the four hipline depths. The string was removed after each tape measurement replication. For the second tape measure replication, the hipline string was again tied or pinned onto the dress form object. To reduce time using the tape measure and to decrease biases from seeing written numbers, tape measurements (Figure 8) were verbalized by the operator and recorded by the researcher. When measuring with the digitizer, operators were instructed to digitize 24 vertical lines in the downward direction: one along the left-side seam, five vertical lines in that quadrant, then along the back seam, five vertical lines in the next quadrant, and continuing this sequence with the right-side seam, five vertical lines in the third quadrant, front seam, and five vertical lines in the last quadrant (Figure 9).

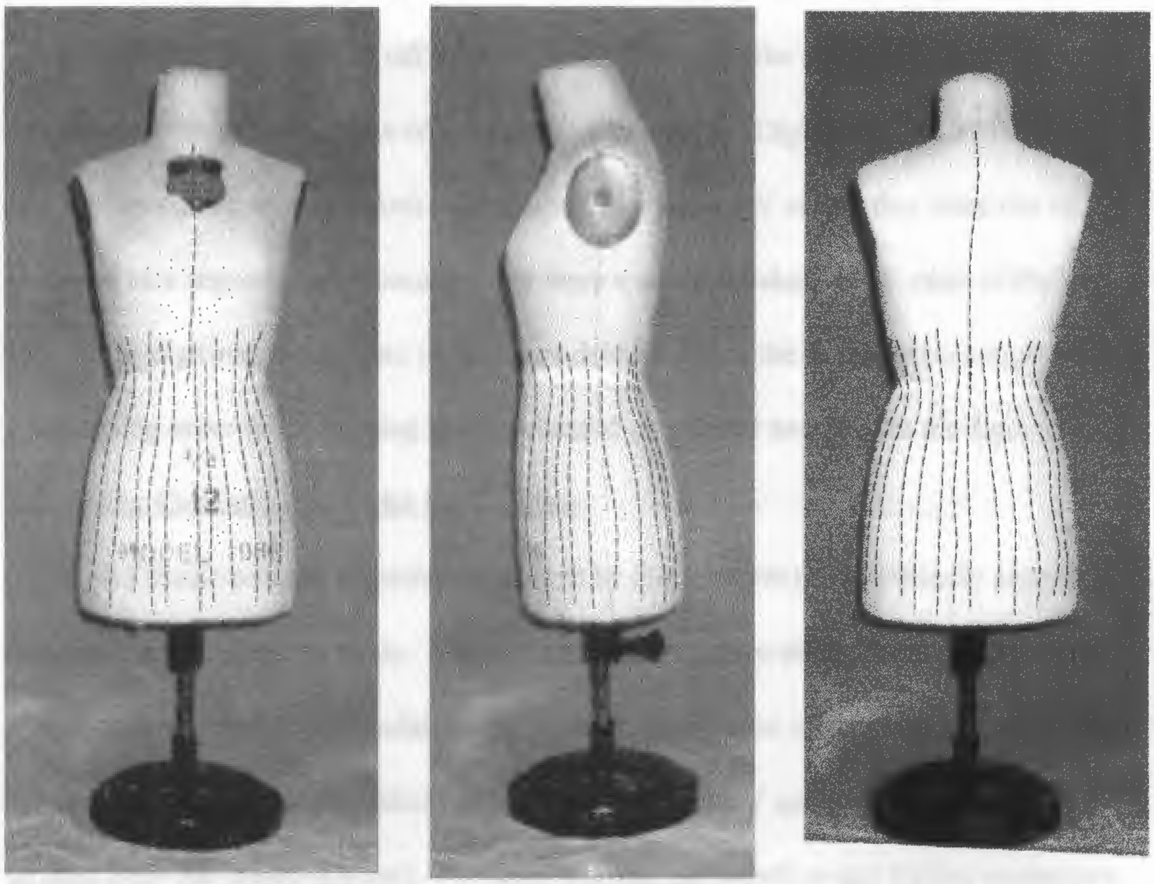
ASCII Data Files into Complex Three-Dimensional Object Measurements

ASCII data files were obtained for each of the measurements. The ASCII data files were the X,Y,Z coordinates, which were continuous without a hard return at the end of each record. The following steps were then used to edit each data file before the final results were calculated: (a) hard returns were entered at the end of each X,Y,Z coordinate



front side back

Figure 8. Measurement of a complex object, a dress form, with a tape measure. A string was tied at the hipline. Measurements were made for waistline, hipline, hipline depths (left, back, right, front), center front, and center back.



front side back

Figure 9. Measurement of a complex object, a dress form, with a digitizer. Twenty-four vertical lines (12 per front and 12 per back, or 6 per quadrant) were drawn beginning below the bustline to the base. Two vertical lines, center front and center back, were digitized from the neckline to the waistline.

series; this was because when the raw data files had been first merged into the CADD program, the visual image did not make sense; (b) a blank line was added between each series of numbers in a digitizer surface sweep; this was done to disconnect each last point when the digitizer was turned off from the first point when the digitizer was turned on; and (c) extraneous points were edited as recommended in "Digitizing with less" (1994).

The editing of extraneous points included changing Y values that were out of sequence to a negative value because they were a positive value. Next, each of the two ends of the digitized sweep data points were deleted where the X values no longer were in a decreasing order (an increasing order indicated an upward sweep with the digitizer).

Calculating Circumferences with the Digitizer

A QBasic program, which was written by Gilpin (1996) to statistically analyze the data was employed in this study. The program accomplishes this by locating the center Y,Z coordinates and then calculating the X levels where most of the Y and Z points were the closest to the center (waistline) and where most of the Y and Z points were the farthest from the center (hipline). At these X levels, the waistline and hipline perimeters were calculated (Appendix D).

Calculating Lengths with the Digitizer

The hipline depths, center front, and center back lengths were calculated using a CADD program. After the data files were imported into DesignCAD 3D, the lines of the center front and center back were calculated for length. The remaining lines were connected to form a surface figure. Frontal (divides front and back) and sagittal (divides left and right) circular planes intersected the surface, and curved lines were traced over the intersection markings. The curved lines were broken at the waistline level and at the hipline level. The line segments between the waistline and hipline were measured for left hipline depth, back hipline depth, right hipline depth, and front hipline depth.

Statistical Methods

The problem was to compare the reliability of data from measurements at eight complex human body locations (waistline circumference, hipline circumference, left hipline depth, back hipline depth, right hipline depth, front hipline depth, center front, and center back). Two tools (tape measure and digitizer) were used and two replications of each measurement were made by the operators. The hypotheses were:

H_1 Data from measurements with the digitizer vary less than data from measurements with a tape measure at the 0.05 level of significance.

H_2 The data from eight complex surface measurements taken with a digitizer vary less than data from a tape measure at the 0.05 level of significance.

The 2 x 8 (tool x location measurement) design included operators who made 2 observations for each of eight locations. The two observations were averaged, and the means were analyzed using the analysis of variance (ANOVA), which is a statistical test for quantitative data with more than two groups and two factors (Witte, 1989). The tabular minimum F values (Witte, 1989) at the 0.05 level were compared to the analysis F values. Analysis F values equal to or greater than the tabular minimum F values would be statistically significant.

The Levene's ANOVA Transformation was used, as suggested by A. R. Gilpin (personal communication, March 1996), to examine variances because it enabled a comparison of the mean deviations from each complex location's deviation (Levene, 1990). The two-way ANOVA was initially used to look at the variances of the measurements. The Levene test was then used to look at the variance of the variances of the measurements. The Levene transformation replaced X by X' so that $X' = (X-\overline{X})^2$. The X was the average measurement of the two replications per operator (where measurements were missing, the group average was used), $\overline{X}$ was the group average, and $X-\overline{X}$ was the deviation, which was squared. The analysis F values were deemed significant if they were equal to or greater than the tabular minimum F value at the 0.05 level (Witte, 1989).

CHAPTER IV

RESULTS

This chapter contains the results of measuring a complex, three-dimensional object, a size 12 one-half-size dress form. The purpose of these measurements was to determine the reliability (variability) of measurements with two tools (tape measure, digitizer) at eight locations on the complex object. The hypotheses of the study were:

H_1 Data from measurements with the digitizer vary less than data from measurements with a tape measure at the 0.05 level of significance.

H_2 The data from eight complex surface measurements taken with a digitizer vary less than data from a tape measure at the 0.05 level of significance.

Survey Results

Operators, an independent variable, came from the textile and clothing department at Iowa State University and included staff, graduate students, retired professors, and their friends or neighbors who were experienced with measuring the human form with a tape measure. All met the established criteria for being an operator because they had experience measuring the human form. Their years of sewing experience ranged from 0 to 54 years with a mean of 32 years. Operators had measured a human form an average of 417 times with a range from 10 to 1000+. Only one operator had previously used a digitizer.

The survey provided an indication of how the operators learned to measure the human form. According to the survey, eight people learned to measure in college; eight learned in high school, and seven learned to measure from professional experience. In addition, five people learned the science of measuring from pattern instructions, and four became knowledgeable on the subject from sewing books. Three operators learned to measure from experiences in 4-H, junior high, and continuing education. Two people had learned to measure a human form from a relative, through volunteer work, and informally at home.

Measurement Results

Eleven operators measured the complex, three-dimensional object four times: twice with the tape measure and twice with the sonic digitizer. Measurements from both tools were entered into a spread sheet for the statistical analysis.

Before the digitizer measurements could be extracted and compared to the tape measurements, the digitizer files had to be edited. Before editing, the continuous digitizer data in CADD produced a very rough visual image as shown in Figure 10. After hard returns were added after each (X,Y,Z) set of numbers, the digitizer data produced CADD drawings as shown in Figure 11.

Most digitizer data had a few Y coordinates that were out of sequence such as: -11, -12, -13, ***14***, -15, -16 which resulted in the extraneous lines as shown in Figure 11. Here, the positive numbers were changed to sequential negative numbers, which were appropriate for extraneous data ("Digitizing with less," 1994). Digitizing the complex, three-dimensional object in a downward direction placed the X coordinates in a decreasing sequential order. When the number flow in the X column changed to a considerably larger number, a new line was created. The points measuring air space (measuring the opposite

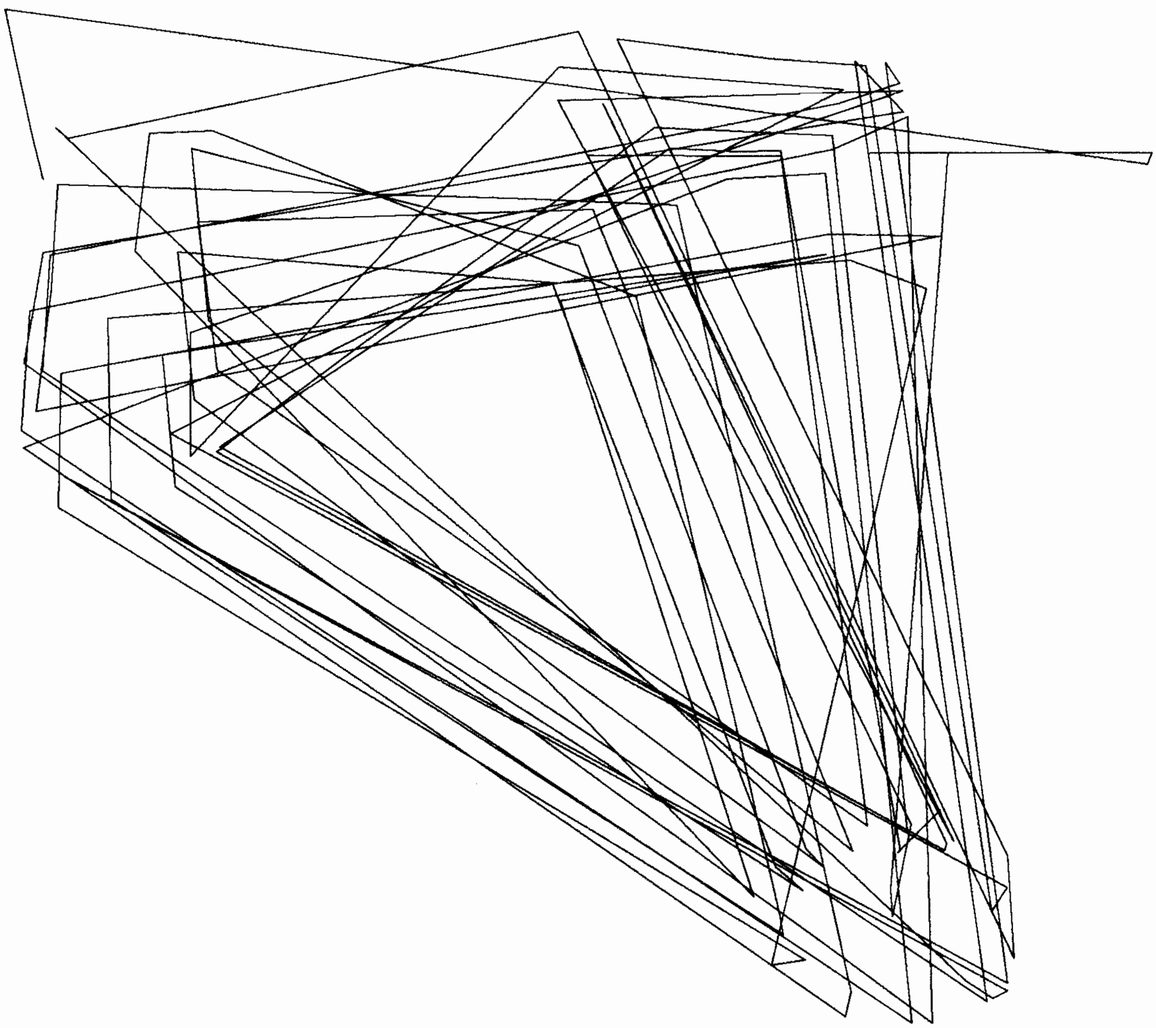


Figure 10. The raw digitizer data needed a hard return after each (X,Y,Z) set of data points. The data shown here were produced before a hard return was inserted.

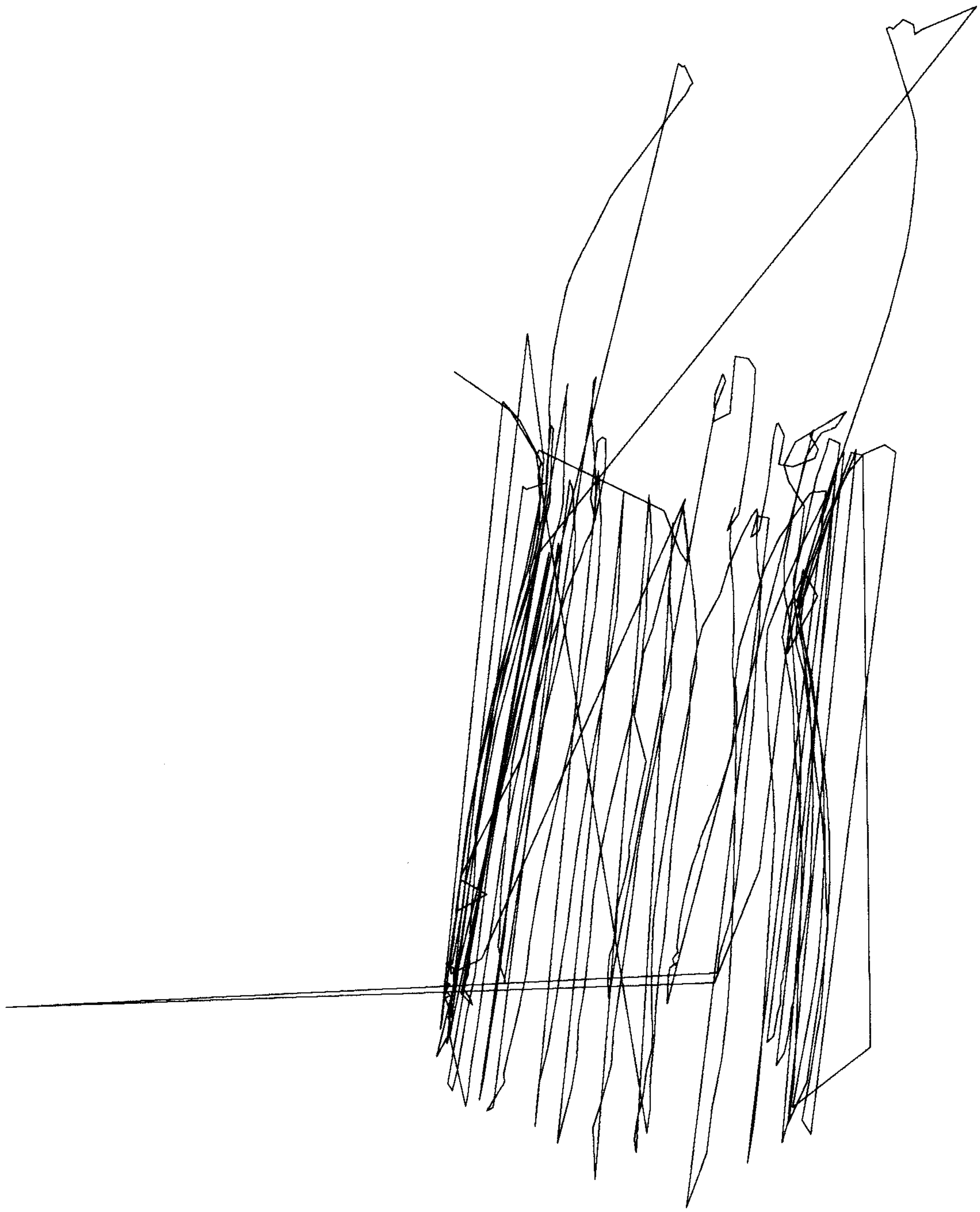


Figure 11. Positive numbers in the Y column (the point on the far left) should be changed to negative values to fit in sequence. Data recorded in reverse order (between the line segments) need to be removed.

direction in the X column) were removed only if they were at the beginning or the end of each line. Occasionally, a larger number increment occurred when the operator forgot to turn off the digitizer tool, pulled the probe off the surface, and then raised the probe to begin another surface recording. Digitizer data, which was edited as mentioned above, produced a drawing shown in Figure 12. The lines were then connected to form a smooth curved surface, and the lines of intersection were drawn between the smooth surface and frontal or sagittal planes as shown in Figure 13.

The ranges of data measurements (in inches) with the tape measure (Table 1) were as follows: waistline 13.81 to 14.45, hipline 17.03 to 19.69, left hipline depth 1.38 to 7.5, back hipline depth 1.38 to 6.89, right hipline depth 1.38 to 7.13, front hipline depth 1.25 to 7.48, center front 7.00 to 7.63, and center back 8.13 to 8.88 inches.

The ranges of data measurements (in inches) with the digitizer (Table 2) were as follows: waistline 13.20 to 15.72, hipline 18.89 to 22.08, left hipline depth 5.56 to 6.71, back hipline depth 5.50 to 6.61, right hipline depth 5.50 to 6.57, front hipline depth 5.46 to 6.57, center front 7.21 to 9.82, and center back 8.12 to 12.29 inches. The means and standard deviations of the tape measure and the digitizer are listed in Table 3. The variance means with the tape measure and the digitizer over location with Levene's test are listed in Table 4 and graphed in Figure 14.

Figure 12. The digitizer data prepared for analysis. Hard returns were added to the end of each record, positive Y values were changed to negative Y values, and points recorded in the reverse X direction between line segments were removed.

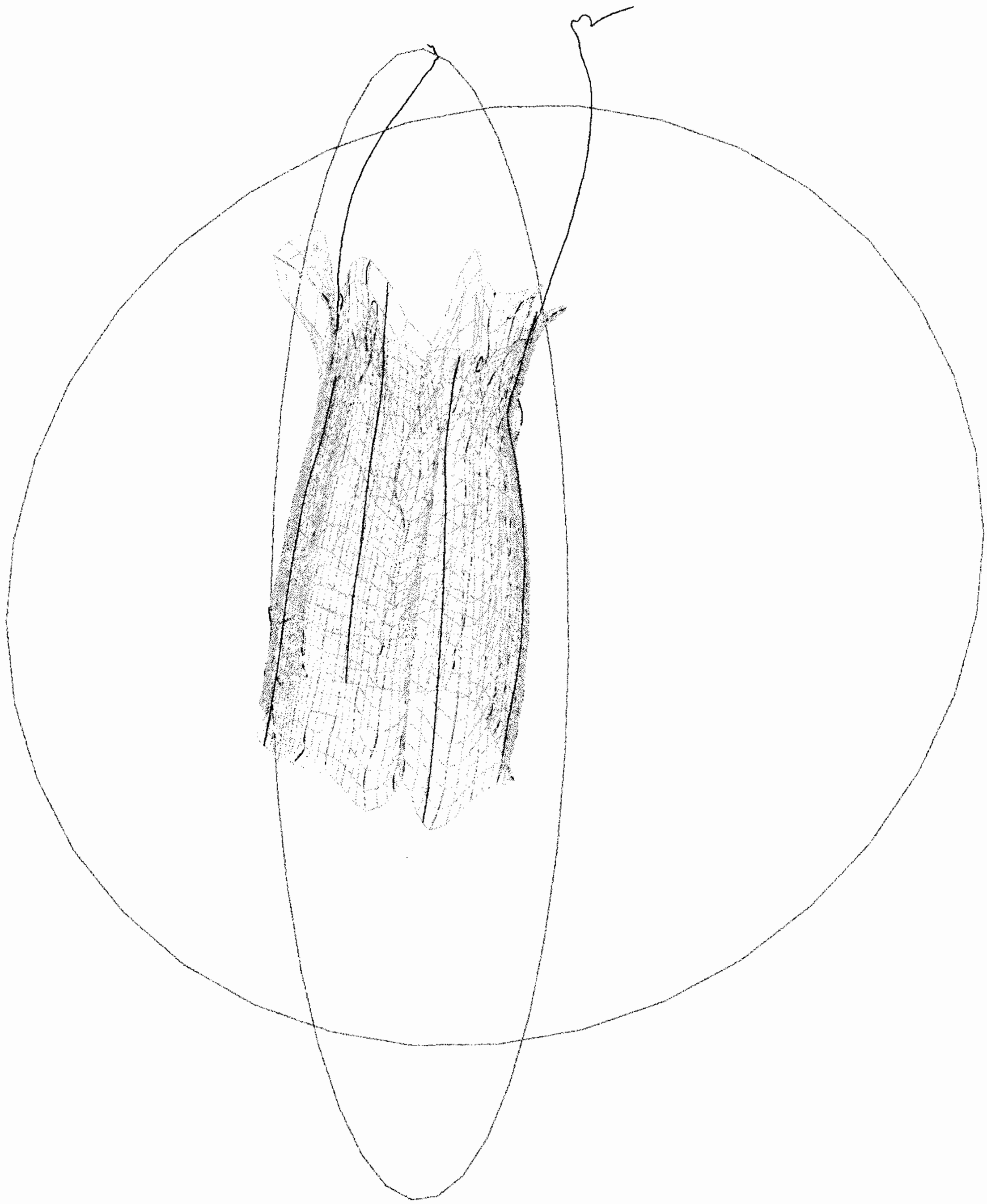


Figure 13. The prepared digitizer data were connected to create a smooth-surface figure. The curved intersection lines from the surface with the frontal and sagittal planes were used in the measurement of the hipline depths.

Table 1

Tape Measurements by Operator, Replication, and Location

					Hipline Depth					
Operator	Rep	Tool	Waistline	Hipline	Left	Back	Right	Front	Center Front	Center Back
1	1	tape	14.45	19.69	4.61	4.21	4.35	4.65	7.28	8.23
1	2	tape	13.81	19.25	4.00	3.81	4.00	4.00	7.38	8.31
2	1	tape	14.00	19.13	4.75	4.25	4.63	4.88	7.13	8.13
2	2	tape	13.98	19.09	4.72	4.33	4.53	4.72	7.09	8.19
3	1	tape	14.00	19.29	7.48	6.77	7.09	7.48	7.09	8.19
3	2	tape	14.00	19.50	7.50	6.88	7.13	7.00	7.06	8.25
4	1	tape	14.00	17.13	1.38	1.38	1.38	1.25	7.38	8.38
4	2	tape	13.98	17.03	1.77	1.57	1.67	1.67	7.28	8.46
5	1	tape	14.00	19.38	4.25	4.25	4.38	4.38	7.63	8.38
5	2	tape	13.98	19.29	4.21	4.02	4.25	4.29	7.32	8.39
6	1	tape	14.00	19.63	6.00	5.50	6.00	5.75	7.50	8.88
6	2	tape	13.98	19.61	5.98	5.59	5.98	5.91	7.60	8.66
7	1	tape	14.07	18.88	3.88	3.50	3.50	3.88	7.50	8.38
7	2	tape	13.98	18.03	2.60	2.05	2.28	2.64	7.28	8.39
8	1	tape	14.00	19.25	4.25	4.13	4.31	4.50	7.25	8.38
8	2	tape	13.98	19.29	4.72	4.25	4.33	4.53	7.36	8.39
9	1	tape	13.98	18.11	7.09	6.89	6.89	7.09	7.09	8.27
9	2	tape	14.00	18.00	2.75	2.38	2.50	2.50	7.00	8.13
10	1	tape	13.98	19.29	3.94	3.74	3.94	3.94	7.32	8.35
10	2	tape	14.00	19.00	4.00	3.63	3.88	4.00	7.38	8.38
11	1	tape	14.00	19.00	3.25	3.00	3.25	3.50	7.50	8.25
11	2	tape	13.98	19.00	3.74	3.54	3.74	3.74	7.48	8.27

Table 2

Digitizer Measurements by Operator, Replication, and Location

Operator	Rep	Tool	Waistline	Hipline	Hipline Depth: Left	Hipline Depth: Back	Hipline Depth: Right	Hipline Depth: Front	Center Front	Center Back
1	1	digitizer	13.23	18.95	6.57	6.51	6.53	6.34		
1	2	digitizer	13.21	19.40	6.30	6.26	6.32	6.22		
2	1	digitizer	13.59	20.75	6.53	6.45	6.52	6.42		
2	2	digitizer	13.78	18.95	6.39	6.31	6.35	6.28	7.21	8.12
3	1	digitizer	13.20	18.89	5.97	5.81	5.90	5.77	7.46	8.90
3	2	digitizer	13.31	20.34	6.11	6.03	6.07	5.99	9.82	9.33
4	1	digitizer	15.72	20.67	6.15	6.07	6.09	6.05	8.03	9.20
4	2	digitizer	14.44	21.06	6.20	6.11	6.16	6.09		
5	1	digitizer	13.97	20.40	6.19	6.09	6.09	6.06		
5	2	digitizer	14.09	21.74	6.37	6.29	6.32	6.27	7.52	8.97
6	1	digitizer	13.56	19.80	6.49	6.38	6.42	6.37	7.82	9.28
6	2	digitizer	13.55	19.51	6.30	6.22	6.25	6.18		
7	1	digitizer	13.96	22.08	5.56	5.50	5.50	5.46	7.90	10.39
7	2	digitizer	13.39	19.43	6.52	6.42	6.47	6.39	8.20	9.3
8	1	digitizer	14.74	20.61	6.56	6.51	6.49	6.44	7.30	8.28
8	2	digitizer	13.91	20.27	6.71	6.57	6.57	6.56	7.38	8.53
9	1	digitizer	13.23	19.18	6.62	6.47	6.54	6.48	7.40	12.29
9	2	digitizer	13.21	19.41	6.30	6.20	6.21	6.17	7.76	12.05
10	1	digitizer	13.79	19.44	6.26	6.19	6.22	6.15	7.66	8.54
10	2	digitizer	13.86	19.59	6.70	6.61	6.32	6.57	7.50	8.43
11	1	digitizer	14.60	21.56	6.56	6.35	6.38	6.33	7.35	8.48
11	2	digitizer	14.48	20.89	6.16	6.09	6.06	6.04	7.38	8.53

Table 3. Measurement Mean and Standard Deviation with Two Tools over Location using ANOVA

	Tape Measure		Digitizer	
Location	Mean	S.D.	Mean	S.D.
Waistline	14.01	0.04	13.86	0.59
Hipline	18.90	0.76	20.13	0.75
Left Hipline Depth	4.40	1.51	6.34	0.19
Back Hipline Depth	4.08	1.39	6.25	0.19
Right Hipline Depth	4.27	1.47	6.26	0.18
Front Hipline Depth	4.38	1.46	6.21	0.19
Center Front	7.31	0.17	7.73	0.37
Center Back	8.35	0.17	9.29	1.05

Table 4. Variance Mean and Standard Deviation with Two Tools over Location using Levene's Test $(X-\overline{X})^2$

	Tape Measure		Digitizer	
Location	Mean	S.D.	Mean	S.D.
Waistline	0.00	0.00	0.32	0.43
Hipline	0.52	0.95	0.52	0.37
Left Hipline Depth	2.07	3.41	0.03	0.04
Back Hipline Depth	1.76	2.77	0.03	0.04
Right Hipline Depth	1.95	3.04	0.03	0.03
Front Hipline Depth	1.93	3.24	0.03	0.04
Center Front	0.03	0.03	0.12	0.24
Center Back	0.02	0.05	1.00	2.44

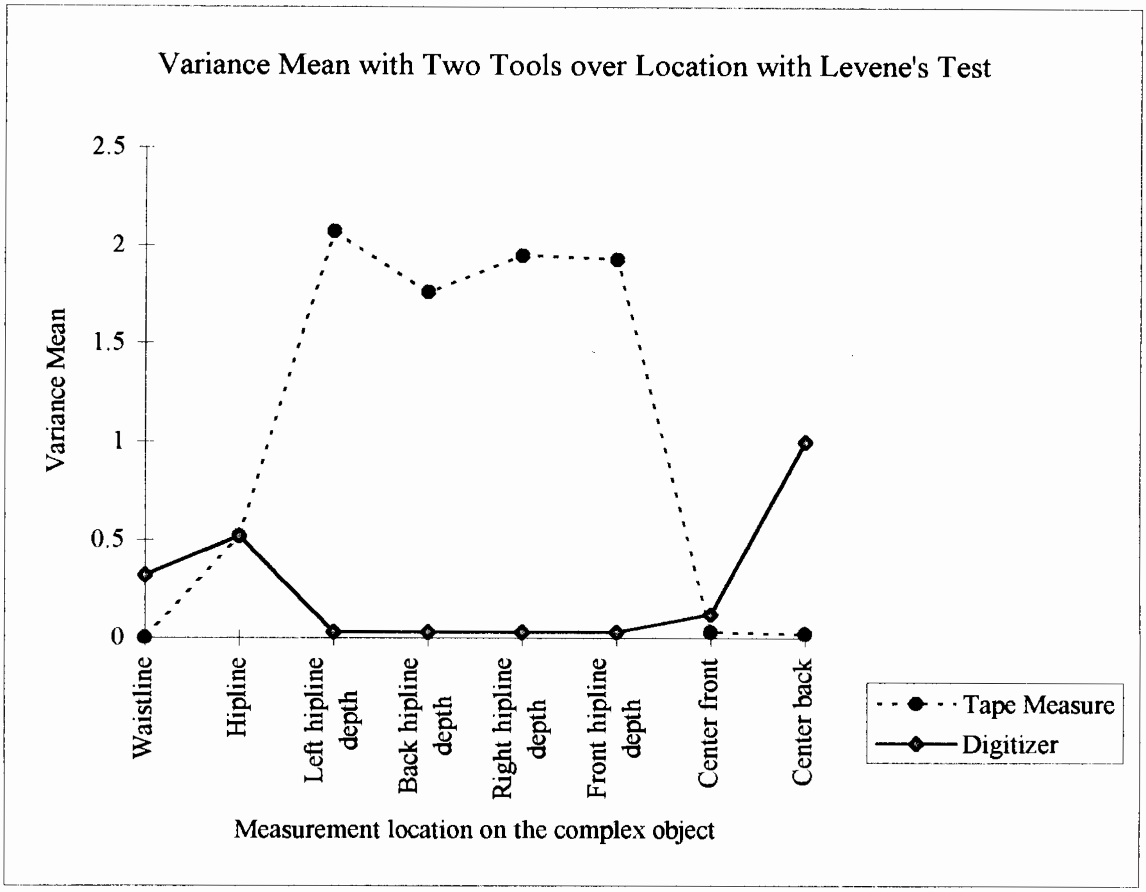


Figure 14. Levene's transformation on mean variances $(X-\overline{X})^2$ with two tools: the sonic digitizer and the tape measure over location on a complex object.

Statistical Results

A two-way ANOVA test (Witte, 1989) was performed on the means of the two tools (tape, digitizer) over location. The analysis F values were compared to the tabular minimum F values and analysis F values equal or greater than the tabular values were deemed significant. Because the main effect, tool by location, was significant, the tool by location simple effects were examined further (Table 5).

Table 5

ANOVA of Means for Tool and Location

ANOVA on Means	Degrees of Freedom	Minimum F value at 0.05	Analysis F Value	Mean Significance
Tool	10	$F_{.05}(1,10)=4.96$	3.10	n.s.
Location	70	$F_{.05}(7,70)=2.14$	1222.24	*
Tool by Location	70	$F_{.05}(7,70)=2.14$	9.70	*
Simple effects of:				
Tool at Waistline		$F_{.05}(1,150)=3.91$	0.20	n.s.
Tool at Hipline		$F_{.05}(1,150)=3.91$	13.31	*
Tool at Left Hipline Depth		$F_{.05}(1,150)=3.91$	33.10	*
Tool at Back Hipline Depth		$F_{.05}(1,150)=3.91$	41.52	*
Tool at Right Hipline Depth		$F_{.05}(1,150)=3.91$	34.86	*
Tool at Front Hipline Depth		$F_{.05}(1,150)=3.91$	29.59	*
Tool at Center Front		$F_{.05}(1,150)=3.91$	1.53	n.s.
Tool at Center Back		$F_{.05}(1,150)=3.91$	7.81	*

Note: * Means are significantly different at the 0.05 level, n.s. Not Significant

Levene's test (Levene, 1990) was employed to examine differences in variability $(X-\overline{X})^2$. To be significant, the analysis F value needed to be greater than or equal to the tabular F value at the 0.05 level (Table 6).

Table 6

Levene's ANOVA Test $(X-\overline{X})^2$ for Tool and Location

Levene's Transformation $(X-\overline{X})^2$.	Degrees of Freedom	Minimum F value at 0.05	Analysis F Value	Mean Significance
Tool	10	$F_{.05}(1,10)=4.96$	11.29	*
Location	70	$F_{.05}(7,70)\approx 2.14$	1.85	n.s.
Tool by Location	70	$F_{.05}(7,70)=2.14$	5.03	*
Simple effects of:				
Tool at Waistline		$F_{.05}(1,150)=3.91$	0.24	n.s.
Tool at Hipline		$F_{.05}(1,150)=3.91$	0.00	n.s.
Tool at Left Hipline Depth		$F_{.05}(1,150)=3.91$	9.70	*
Tool at Back Hipline Depth		$F_{.05}(1,150)=3.91$	6.91	*
Tool at Right Hipline Depth		$F_{.05}(1,150)=3.91$	8.60	*
Tool at Front Hipline Depth		$F_{.05}(1,150)=3.91$	8.32	*
Tool at Center Front		$F_{.05}(1,150)=3.91$	0.02	n.s.
Tool at Center Back		$F_{.05}(1,150)=3.91$	2.23	n.s.

Note: * $(X-\overline{X})^2$ significantly different at 0.05 level, n.s. Not Significant

For the analysis of variance of means shown in Table 5, the main effect for tool was not significant at the 0.05 level. This indicated digitizer measurements made over all of the object were similar to measurements made with a tape measure. However, two effects, location alone and tool by location, were significant at the 0.05 level.

After examining simple effects of tool by location, it was determined that five locations on the complex object had significantly different mean data measurements collected with the digitizer as compared to those collected with a tape measure. The five significant (at the 0.05 level) simple effects for hipline, left hipline depth, back hipline depth, right hipline depth, and front hipline depth, indicated that digitizer measurements were smaller than those made with the tape measure. In contrast, the center back location measurements were smaller with the tape measure tool than those made with the digitizer tool. Center front measurements were similar with both tools (no significant difference).

Differences for the variances with the digitizer and the tape measure were significant for some measurement locations as shown in Table 6 which represents Levene's analysis of variance test $(X-\overline{X})^2$ for tool and location. The main effect of the tool was significant at the 0.05 level. Here there was less variability in the overall measurement data with a digitizer than with a tape measure. The main effect of location was not significant at the 0.05 level. However, the tool by location interaction was significant, and simple effects were therefore examined. Differences in variation between the digitizer and tape measure for tool by four locations (simple effects) were significant at the 0.05 level, favoring the digitizer for the following four data locations: left hipline depth, back hipline depth, right hipline depth, and front hipline depth. Four simple effects (tool at center back, tool at center front, tool at waistline, and tool at hipline) were not significant for the Levene's test of the variances in the measurement data.

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary and Discussion

Measurements of a complex object were taken with a sonic digitizer and a tape measure and compared. The statistical analysis indicated the tools and tool x location measurements were significant. For individual locations, (hipline, hipline depths, and center back), measurements were significantly different between the sonic digitizer and a tape measure. However, the waistline and the center front were not significant between tools.

For measurement variation, the ANOVA was used; for analyzing the variations, Levene's test was used. The tool variations of measurement were significant at the 0.05 level when analyzed using the Levene's test, but not with ANOVA analyzing the differences of measurement. However, the tool by location effect was significant with both the ANOVA and Levene's tests. Because this tool by location effect was significant, the interaction was examined further for simple effects.

Variations and actual measurement differences for waistline measurements with the digitizer and the tape measure were not statistically significant. The waistlines measured by the digitizer were calculated using a computer. The waistlines measured with the tape measure were measured around an area marked with a grosgrain ribbon. This marking contributed to the measurement similarity of the two tools.

The hipline measurement was statistically significant with the ANOVA test at the 0.05 level. Again, hipline measurements made with the digitizer were calculated by the computer. When making a tape measurement, locating the hipline, which was an unmarked location, required a subjective judgement by the operator. As expected, there was more variability when measuring with the tape measure than when measuring with the digitizer. This variation in measurement with a tape measure agrees with the variations for measurement devices as found in previous studies (Staples et al., 1994 and Sheldon, 1963). Variations observed from the tape measurements indicated that there were variations in the subjective hipline string placement.

Differences in the operator measurements of the left hipline depth, back hipline depth, right hipline depth, and front hipline depth and differences of the variations of the measurements were significant at the 0.05 level with the ANOVA and the Levene tests, respectively. Operators reproduced similar measurements with the digitizer, but not with the tape measure. With the digitizer, hipline depth measurements were derived from the statistically calculated hipline and waistline locations and by measuring the surface distance from the waistline to the hipline.

For these left hipline depth, back hipline depth, right hipline depth, and front hipline depth measurements, it became apparent that the hipline location was subjective for tape measurement. The study began with the waistline location well marked with a grosgrain ribbon and the left, back, right, and front marked by seams. However, the hipline location was unmarked and therefore was a subjective location for the operators to locate.

The center front location was not significantly different for differences in tool measurements. Here, measurement data from the digitizer had extraneous points, but these points did not statistically affect the variations between the digitizer and tape measurements. Since the area to tape measure was a well defined location by the intersection of a seam and the grosgrain ribbon, the variations in measurement were minimized for both tools.

The center back measurements were significantly different between tools at the 0.05 significance level with the ANOVA test, but the variations between the two tools measurements were not significant with the Levene's test. The mean variance for measurements of the center back was greater for the digitizer than for the tape measure. Here again the area to tape measure was well marked. Viewing the digitizer measurements in the CADD program, one could observe excess lines within the center front and center back digitizer measurements. Excess points within a line came about in one of the following four ways: (a) turning on the digitizer too soon, (b) turning off the digitizer too late, (c) positioning the probe tip so it caught (snagged) the fabric surface, and (d) starting over in the middle of a measurement. These extra points were all possibly due to the inexperience of the operators. To produce consistent measurements, it would be necessary to do further editing of the digitizer data to remove some extraneous numbers. However, to maintain uniformity in treating the data files, guidelines or rules for what to edit and how to edit needs to be made beyond the initial adjustments.

This study was valuable in that it provided research to support the supposition that measuring a complex, three-dimensional object such as the human body, especially complex locations such as hipline and hipline depths, can be done more accurately with the digitizer. Even with operators familiar with using the traditional tool (each had tape measured the human form an average of 417 times and had digitized the human form 0 times), the digitizer was a better measuring tool than the tape measure for most locations.

Conclusions

The objective of this study was to compare the measurement reliability of a sonic digitizer to a traditional measuring tool, the tape measure, for measuring a complex, three-dimensional object. It was hypothesized that:

H_1 Data from measurements with the digitizer vary less than data from measurements with a tape measure at the 0.05 level of significance.

H_2 The data from eight complex surface measurements taken with a digitizer vary less than data from a tape measure at the 0.05 level of significance.

Data from measurements with the digitizer varied less than data from measurements with a tape measure at the 0.05 level of significance. The measurements with the two tools did not show overall differences in mean values when examined with a two-way analysis of variance, but when using the Levene's analysis of variance transformation, variances of tool effects were significant. Based on the statistical analysis, hypothesis H_1 was supported by the results and was accepted.

Regarding hypothesis H_2, the data from eight complex surface measurements taken with a digitizer varied less than data from a tape measure at the 0.05 level of significance. The digitizer was a more reliable (i.e., showed less variability) measurement tool than a tape measure for five measurement locations on the complex object. This reliability was even higher for the object's hard-to-define areas. Measurement data from one location, center front, with body landmarks had less variability with the tape measure than with the digitizer tool. This was most likely due to data caused by inexperience with the digitizer tool. Thus, hypothesis H_2 was retained. One should note that by location, the hypothesis H_2 could not be accepted in every case, but overall H_2 could be accepted.

Recommendations

It is recommended for future studies that operators have more practice turning the digitizer probe on and off and holding the digitizer to the complex objects surface at crucial locations. The amount of extraneous data might be diminished with experienced operators. In addition, it is recommended that the operators measure the complex three-dimensional object for at least three replications. When more measurements are averaged, the results should be more accurate (Witte, 1989).

Since operators wanted to rotate the complex, three-dimensional object instead of walking around it, it is recommended for a future study to determine a way to have the object placed on a rotating wheel. When the operators were to digitize or tape measure the complex object, many asked if they could turn the object. When traditional tape measuring a human, the operator would remain stationary, and the human would turn. In this instance, using a digitizer, the object had to remain stationary.

A third recommendation is to create a microphone frame mounted on the ceiling from which the far side of the complex object might have fewer sound waves blocked when measured. Mounting the microphone frame on the ceiling might lessen the extraneous data because it would permit the user to hold the probe naturally instead of holding the probe at an awkward tilt while striving to position the top mounted sound emitters in the direction of a wall frame.

Suggestions for future studies are as follows: (a) duplicate this study using other complex three-dimensional forms, (b) duplicate this study measuring other body locations on a dress form, (c) duplicate this study on one or more live persons, (d) duplicate this study and determine the minimum number of sweeps per location for acceptable measurements, (e) study the learning curve associated with becoming proficient in using the digitizer, and (f) compare the reliability of different types of scanners and digitizers.

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APPENDIX

APPENDIX A

Addresses for Digitizer and Scanner Manufacturers and Other Suppliers

The names and addresses for the digitizer and scanner manufacturers in Figure 1 (Chapter II, Review of literature) are listed below. Other suppliers such as Engineering Animation, SIGGRAPH, and Superior Model Forms are included.

Cyberware Laboratory Inc. (1996). [a laser scanner manufacturer]. 2110 Del Monte Avenue. Monterey, CA 93940. Telephone (408) 373-1441. Fax (408) 373-3582. Web address: http://www.cyberware.com.

Digi-botics. (1993). [a laser scanner manufacturer]. 2800 Longhorn Blvd., Suite 102. Austin, TX 78758. Telephone (512) 832-6544. Fax (512) 832-1163.

Engineering Animation, Inc. (1996). [the company who graciously allowed the use of their sonic digitizer and office for this study]. 2625 North Loop Drive. Ames, IA 50010. Telephone (515) 296-9908. Fax (515) 296-7025.

FARO Technologies Inc. (1995). [a mechanical digitizer manufacturer]. 125 Technology Park. Lake Mary, FL 32746. Telephone (407) 333-9911. Fax (407) 333-4181.

Geodetic Services, Inc. (1996). [a photogrammetric scanner manufacturer]. 1511 South Riverview Drive; Melbourne, FL 32901. Telephone (407) 724-6831. Fax (407) 724-9253.

GTCO Corp. (1995). [a sonic digitizer manufacturer, now owns SAC]. 7125 Riverwood Dr., Columbia, MD 21046. Telephone (401) 381-6688. Fax (401) 290-9065.

Hymarc, LTD. (1995). [a laser scanner manufacturer]. 38 Auriga Drive; Ottawa, ON, Canada K2E 8A5. Telephone (613) 727-1584. Fax (613) 727-0441. E-mail: info-@hymarc.com.

Image Guided Technology. (1995). [a light digitizer manufacturer, formerly Pixsys]. 1727 Conestoga, Boulder, CO 80301. Telephone (303) 447-0248. Fax (303) 447-3905.

Imetric SA. (1996). [a photogrammetry manufacturer, also known as Komeg]. Rue du Bourg 9, CH-2892 Courgenay, Switzerland. Telephone 41 66 712312. Fax 41 66 712976.

Immersion Corporation. (1996). [a mechanical digitizer manufacturer]. 2158 Paragon Drive; San Jose, CA 95131. Telephone (408) 467-1900. Fax (408) 467-1901. E-Mail: immersion@starconn.com. Web address: http://www.immerse.com.

Laser Design Inc. (1996). [a laser scanner manufacturer]. 9401 James Avenue South, Suite 162; Minneapolis, MN 55431. Telephone (612) 884-9648. Fax (612) 884-9653.

Perceptron USA. (1996). [a laser scanner manufacturer]. 23855 Research Drive, Farmington Hills, MI 48335-2643. Telephone (810) 478-7710. Fax (810) 478-7059.

Pixsys. (1993). [a light digitizer manufacturer now called Image Guided Technology]. 1727 Conestoga, Boulder, CO 80301. Telephone (303) 447-0248. Fax (303) 441-2487.

Polhemus, a Kaiser Aerospace & Electronics Company. (1996). [an electro-magnetic digitizer manufacturer]. P.O. Box 560. Colchester, VT 05466. Telephone (802) 655-3159. Fax (802) 655-1439.

Romer Supratech Incorporated. (1996). [a mechanical digitizer manufacturer]. 5145 Avenida Encinas. Carlsbad, CA 92008. Telephone (619) 438-1725. Fax (619) 438-3512. Sales: 806 Oakwood Blvd., Dearborn, MI 48124. Telephone (313) 563-5933. Fax (313) 274-9623. E-mail: romerinc@adnc.com Web address: http://www.romer.com.

Science Accessories Corporation. (1995). [a sonic digitizer manufacturer, see GTCO].

Sharnona Corporation. (1995). [a laser digitizer manufacturer]. 45901 Five Mile Road. Plymouth, MI 48170. Telephone (313) 454-7192. Fax (313) 454-7198.

SIGGRAPH. (1993) [a graphics trade show] 401 North Michigan Avenue; Chicago, IL 60611. Telephone (312) 644-6610. Fax (312) 321-6876.

SpacialMetriX Corporation (SMX). (1995). [a laser scanner manufacturer]. 222 Gale Lane. Kennett Square, PA 19348. Telephone (610) 444-2300. Fax (610) 444-2323.

Spatial Positioning Systems (SPS). (1996). [a laser scanner manufacturer]. 12007 Sunrise Valley Drive, Suite 200; Reston, VA 22091-3406. Telephone (703) 648-9400. Fax (703) 648-9422.

Superior Model Forms Corporation. (1986). [a manufacturer of dress forms] 545 8th Avenue, New York, NY 10018. Telephone (212) 947-3633.

3D Scanners Ltd. (1996). [a laser scanner manufacturer]. South Bank Technopark; 90 London Road; London SE1 6LN, U.K. Telephone 441-71-922-8822. Fax 441-71-922-8899.

APPENDIX B

Measuring the Dress Form Survey

Please complete the survey blanks in the order listed.

Years actively sewing clothing ______ (whole numbers or fractions)
How many times (approximate) have you measured a human form using a tape measure?
______

How did you learn to measure a human form? (Please identify all sources i.e. scouts, 4-H, junior high, high school, college course, continuing education, pattern book or instructions, sewing book, relative, volunteer work, professional experience)

Prior to this research, how many times have you used a digitizer?______
Prior to this survey, how many times (approximate) have you measured this dress form?______

TAPE MEASURE (inches or cm)

START TIME______
WAISTLINE______
HIPLINE______
HIP DEPTH L___ B___ R___ F___
Left side, Right side, Back, Front waistline to hipline
CENTER FRONT_____
CENTER BACK_____
END TIME______

TAPE MEASURE (inches or cm)

START TIME______
WAISTLINE______
HIPLINE______
HIP DEPTH L___ B___ R___ F___
Left side, Right side, Back, Front waistline to hipline
CENTER FRONT_____
CENTER BACK_____
END TIME______

DIGITIZER

START TIME______
WAISTLINE
HIPLINE
CENTER FRONT
CENTER BACK
END TIME______
Save the file as TMT___R___

DIGITIZER

START TIME______
WAISTLINE
HIPLINE
CENTER FRONT
CENTER BACK
END TIME______
Save the file as TMT___R___

TMT = Treatment (survey number) R = Replication number measuring the one-half-size dress form.
Questions, comments, words of wisdom:

APPENDIX C

Human Subject Informed Consent

The purpose of the research is to compare tape measurements to digitizer measurements of a one-half-size dress form. A total of four sets of measurements will be made and recorded: two using a digitizer and two using a tape measure.

One benefit of this study will be to determine if one measurement tool is more reliable than the other. Using a three-dimensional digitizer as a measurement tool could be used to custom fit clothing needed by government and emergency groups, athletes, disabled persons, persons of non-conforming dimensions, and people needing custom apparel.

To maintain confidentiality, data collected on the forms will be not be labeled with names. Completion of the measurements is encouraged. Missing data may void the replication, and the set of data may need to be discarded.

If you have any questions about the research, I (Diane Schou) may be contacted at: (319) 277-4338; fax (319) 266-7569; 6621 West Ridgeway Avenue, Cedar Falls, Iowa 50613. You may also contact my advisor, Dr. Johnson in the Department of Industrial Technology, University of Northern Iowa, (319) 273-2561. For questions about rights of research subjects, you may contact the Human Subjects Coordinator, University of Northern Iowa, (319) 273-2748.

I am fully aware of the nature and extent of my participation in this project as stated above. I hereby agree to participate in this project. I acknowledge that I have received a copy of this consent statement.

____

(Signature of subject or responsible agent) Date

____

(Printed name of subject)

____

(Signature of investigator)

APPENDIX D

A Software Program for Generating Waistline and Hipline Locations and Perimeters

This QBasic program was written for this study by A. R. Gilpin (1996). It is a DOS based program and was run on 486 PC computers.

```
DECLARE SUB SortArray (noitems%)
DECLARE SUB getcart (z!, y!, theta!, radius!)
DECLARE SUB getpolar (z!, y!, theta!, radius!)
DECLARE SUB GetSeries (Series!())

' This program takes a dressform scan and estimates waist and hip
' height and perimeters (estimated from straight lines connecting
' observed points

CONST sen = 100 'sensitivity; ignore any datapoints deviating from adjacent
        'points by more than this proportion
CONST resett = .6 'any datapoints deviating from next value by more than this
           'proportion will indicate last point in a series
CONST minpts = 4 'a series must have this many points to be used

DIM raw(1500, 3)
DIM Series(100, 3)'x,y,z values for a series of points on vertical pass
DIM serieslen%(25) 'number of points for each of 25 series
DIM cart(102, 25, 3)'100 points on 25 series, x,y,z values
DIM polar(360)  'r values corresponding to polar angles
DIM rmin(25, 3), rmax(25, 3)'holds minimum and maximum radius on 25 series
DIM vertmin(25), vertmax(25)'x (vertical) coordinates on 25 series


CLS
INPUT "Input file"; ffspec$
IF ffspec$ = "x" THEN 'for convenience in debugging
  PRINT "debug"
  ffspec$ = "c:\dumper\tmt14r1.dat"
END IF
OPEN ffspec$ FOR INPUT AS #1
```

```
INPUT "Output file"; outspec$
outflag% = 1
IF outspec$ = "" THEN
  outflag% = 0
ELSE
  IF outspec$ = "x" THEN 'for convenience in debugging
    outspec$ = "c:\stats\acrospin\output.acd"
  END IF
  OPEN outspec$ FOR OUTPUT AS #2
  PRINT #2, "PointList X Y Z Color Layer"
END IF


CLS
PRINT "Reading file..."
index% = 0
DO WHILE NOT EOF(1)
  index% = index% + 1
  LINE INPUT #1, buff$
  'parse out 3 coordinates
  commaloc1% = INSTR(buff$, ",")
  x$ = LEFT$(buff$, commaloc1% - 1)
  commaloc2% = INSTR(commaloc1% + 1, buff$, ",")
  y$ = MID$(buff$, commaloc1% + 1, commaloc2% - commaloc1% - 1)
  z$ = MID$(buff$, commaloc2% + 1)
  raw(index%, 1) = VAL(x$)
  raw(index%, 2) = VAL(y$)
  raw(index%, 3) = VAL(z$)
 LOOP
CLOSE #1
PRINT "File read; "; index%; "3-D coordinates were identified."
'at this point the data are in raw(index%,3)

'initial values

seriesstart% = 0
seriescount% = 0
pointcount% = 0
sumx1 = 0
sumy1 = 0
sumz1 = 0
```

```
DO WHILE seriescount% < 25 AND seriesstart% < index%
 PRINT "Attempting to determine series "; seriescount% + 1
 'extract a series
 prevx = raw(seriesstart% + 1, 1)'set to first value of next series
 prevy = raw(seriesstart% + 1, 2)
 prevz = raw(seriesstart% + 1, 3)
 serieslength% = 0
 CALL GetSeries(Series())
 'double check for weird series
 IF serieslength% < minpts THEN 'something went wrong; throw out this series
  GOTO endofloop
 END IF
 IF Series(serieslength%, 1) > 10 THEN 'assume this series doesn't scan to hips
  GOTO endofloop
 END IF

 'series is valid
 seriescount% = seriescount% + 1 'increment series
 serieslen%(seriescount%) = serieslength%
 PRINT "Series "; seriescount%; "contains"; serieslength%; " points."
 PRINT "first values:";
 PRINT Series(1, 1), Series(1, 2), Series(1, 3)
 PRINT "Last values:";
 PRINT Series(serieslength%, 1), Series(serieslength%, 2), Series(serieslength%, 3)

 'store the series in array cart() and accumulate sums
 FOR i% = 1 TO serieslength%
  cart(i%, seriescount%, 1) = Series(i%, 1) 'x (vert)
  cart(i%, seriescount%, 2) = Series(i%, 2) 'y
  cart(i%, seriescount%, 3) = Series(i%, 3) 'z
  pointcount% = pointcount% + 1
  sumx1 = sumx1 + Series(i%, 1)
  sumy1 = sumy1 + Series(i%, 2)
  sumz1 = sumz1 + Series(i%, 3)
 NEXT i%
endofloop:
LOOP
PRINT seriescount%; "vertical series were identified."

'now center the origin inside the figures.
'first compute mean of the seriescount% values at the middlemost scan
PRINT "Centering figure...";
```

```
'we want to subtract the means from all coordinates, to place the origin inside
'note this doesn't affect areas or perimeters
PRINT "Means of "; pointcount%; "points:"
meanx = sumx1 / pointcount%
meany = sumy1 / pointcount%
meanz = sumz1 / pointcount%
PRINT "X:", meanx
PRINT "Y:", meany
PRINT "Z:", meanz
FOR i% = 1 TO seriescount%
 FOR j% = 1 TO serieslen%(i%)
  cart(j%, i%, 2) = cart(j%, i%, 2) - meany
  cart(j%, i%, 3) = cart(j%, i%, 3) - meanz
  IF outflag% = 1 THEN 'print points to file
   PRINT #2, USING "###.###"; cart(j%, i%, 1); cart(j%, i%, 2); cart(j%, i%, 3);
   PRINT #2, " 15 0"
  END IF
 NEXT j%
NEXT i%
PRINT "Figure has been centered at ";
PRINT USING "####.##"; meany; meanz

'now convert the series to coordinates x,theta,radius
FOR i% = 1 TO seriescount%
 PRINT "Finding hip and waist coordinates for series "; i%; "..."
 FOR j% = 1 TO serieslen%(i%)
  Series(j%, 1) = cart(j%, i%, 1) 'get x coordinates for the series
  myy = cart(j%, i%, 2)
  myz = cart(j%, i%, 3)
  CALL getpolar(myy, myz, theta, radius)'get polar coord corresp to y,z
  Series(j%, 2) = theta
  Series(j%, 3) = radius
 NEXT j%

 'now sort the series by radius
 j% = serieslen%(i%)
 CALL SortArray(j%)

 'at this point, Series() contains x,theta,radius sorted by radius
 'store result in rmin() and rmax()
 rmin(i%, 1) = Series(1, 1) 'set rmin to x,theta,radius for minimum radius
 vertmin(i%) = Series(1, 1)
```

```
  rmin(i%, 2) = Series(1, 2)
  rmin(i%, 3) = Series(1, 3)
  rmax(i%, 1) = Series(j%, 1) 'set rmax to x,theta,radius for maximum radius
  vertmax(i%) = Series(j%, 1)
  rmax(i%, 2) = Series(j%, 2)
  rmax(i%, 3) = Series(j%, 3)
NEXT i%

'find mean of all x coordinates for min and max
summinx = 0
countminx% = 0
summmaxx = 0
countmaxx% = 0
FOR i% = 1 TO seriescount%
  myx = rmin(i%, 1)
  summinx = summinx + myx
  countminx% = countminx% + 1
  myx = rmax(i%, 1)
  summaxx = summaxx + myx
  countmaxx% = countmaxx% + 1
NEXT i%
hipmeanx = summaxx / countmaxx% 'xcoordinate of hips
waistmeanx = summinx / countminx% 'xcoordinate of waist

'compute and print the back-transformed coordinates of the waist and hip
minwaistradius = 1000
maxwaistradius = -1000

FOR i% = 1 TO seriescount% 'min
  PRINT "Finding waist coordinates for series"; i%; "..."
  myx = rmin(i%, 1)
  theta = rmin(i%, 2)
  radius = rmin(i%, 3)
  IF radius < minwaistradius THEN
    minwaistradius = radius
  END IF
  IF radius > maxwaistradius THEN
    maxwaistradius = radius
  END IF
  CALL getcart(myy, myz, theta, radius)
  IF outflag% = 1 THEN
    PRINT #2, USING "###.##"; myx; myy; myz;
```

```
   PRINT #2, " 15 0"
  END IF
NEXT i%
'



'do the same thing for hips
minhipradius = 1000
maxhipradius = -1000

FOR i% = 1 TO seriescount% 'max
  PRINT "Finding hip coordinates for series "; i%; "..."
  myx = rmax(i%, 1)
  theta = rmax(i%, 2)
  radius = rmax(i%, 3)
  IF radius < minhipradius THEN
    minhipradius = radius
  END IF
  IF radius > maxhipradius THEN
    maxhipradius = radius
  END IF
  CALL getcart(myy, myz, theta, radius)
  IF outflag% = 1 THEN
    PRINT #2, USING "###.##"; myx; myy; myz;
    PRINT #2, " 15 0"
  END IF
NEXT i%

PRINT "Estimating perimeter for waist..."

'plot the points for the waist
waistlength = 0
FOR i% = 1 TO seriescount%
  theta = rmin(i%, 2)
  radius = rmin(i%, 3)
  CALL getcart(myy, myz, theta, radius)
  starty = myy
  startz = myz
  IF i% < seriescount% THEN
    theta = rmin(i% + 1, 2)
    radius = rmin(i% + 1, 3)
```

```
  ELSE
   theta = rmin(1, 2)
   radius = rmin(1, 3)
  END IF
  CALL getcart(myy, myz, theta, radius)
  stopy = myy
  stopz = myz

  diffy = stopy - starty
  diffz = stopz - startz
  mydistance = SQR(diffy * diffy + diffz * diffz)
  waistlength = waistlength + mydistance

  'plot points along start to stop
  IF stopy > starty THEN
   FOR myy = starty TO stopy STEP .01
    myz = (stopy * startz - starty * stopz - (startz - stopz) * myy) / (stopy - starty)
    IF outflag% = 1 THEN
     PRINT #2, USING "########.###"; waistmeanx; myy; myz;
     PRINT #2, " 15 0"
    END IF
   NEXT myy
  ELSE
   FOR myy = starty TO stopy STEP -.01
    myz = (stopy * startz - starty * stopz - (startz - stopz) * myy) / (stopy - starty)
    IF outflag% = 1 THEN
     PRINT #2, USING "########.###"; waistmeanx; myy; myz;
     PRINT #2, " 15 0"
    END IF
   NEXT myy
  END IF
NEXT i%
PRINT "Waist found at"; waistmeanx; " with perimeter "; waistlength

PRINT "Estimating perimeter for hip..."

'plot the points for the hip
hiplength = 0
FOR i% = 1 TO seriescount%
 theta = rmax(i%, 2)
 radius = rmax(i%, 3)
 CALL getcart(myy, myz, theta, radius)
```

```
  starty = myy
  startz = myz
  IF i% < seriescount% THEN
   theta = rmax(i% + 1, 2)
   radius = rmax(i% + 1, 3)
  ELSE
   theta = rmax(1, 2)
   radius = rmax(1, 3)
  END IF
  CALL getcart(myy, myz, theta, radius)
  stopy = myy
  stopz = myz

  diffy = stopy - starty
  diffz = stopz - startz
  mydistance = SQR(diffy * diffy + diffz * diffz)
  hiplength = hiplength + mydistance

  'plot points along start to stop
  IF stopy > starty THEN
   FOR myy = starty TO stopy STEP .01
    myz = (stopy * startz - starty * stopz - (startz - stopz) * myy) / (stopy - starty)
    IF outflag% = 1 THEN
     PRINT #2, USING "########.###"; hipmeanx; myy; myz;
     PRINT #2, " 15 0"
    END IF
   NEXT myy
  ELSE
   FOR myy = starty TO stopy STEP -.01
    myz = (stopy * startz - starty * stopz - (startz - stopz) * myy) / (stopy - starty)
    IF outflag% = 1 THEN
     PRINT #2, USING "########.###"; hipmeanx; myy; myz;
     PRINT #2, " 15 0"
    END IF
   NEXT myy
  END IF
NEXT i%
PRINT "Hip found at"; hipmeanx; " with perimeter "; hiplength


PRINT "Run complete."
INPUT "Press <Enter> to exit..."; dum$
```

```
CLOSE
STOP

SUB getcart (x, y, theta, radius)
 'return x and y given angle theta and radius radius
 'note theta is in degrees, from 0 through 360 (not typical)
 r# = radius
 ttheta# = theta
 SELECT CASE ttheta#
  CASE IS = 0#
   xx# = r#
   yy# = 0#

  CASE IS = 90#
   xx# = 0#
   yy# = r#
  CASE IS = 180#
   xx# = -1# * r#
   yy# = 0#
  CASE IS = 270#
   xx# = 0#
   yy# = -1# * r#
  CASE ELSE
   rad# = .01745329#'conversion factor, degrees to radians=pi/180
   SELECT CASE ttheta#
    CASE 0# TO 90# 'upper right
     lambda# = ttheta#
     lambdarads# = lambda# * rad#
     xx# = COS(lambdarads#) * r#
     yy# = SIN(lambdarads#) * r#
    CASE 90# TO 180# 'upper left
     lambda# = ttheta# - 90#
     lambdarads# = lambda# * rad#
     xx# = r# * SIN(lambdarads#) * -1#
     yy# = r# * COS(lambdarads#)
    CASE 180# TO 270# ' lower left
     lambda# = ttheta# - 180#
     lambdarads# = lambda# * rad#
     xx# = r# * COS(lambdarads#) * -1#
     yy# = r# * SIN(lambdarads#) * -1#
    CASE ELSE 'lower right
     lambda# = ttheta# - 270#
```

```
        lambdarads# = lambda# * rad#
        xx# = r# * SIN(lambdarads#)
        yy# = r# * COS(lambdarads#) * -1#
    END SELECT
  END SELECT
  x = xx#
  y = yy#
END SUB

SUB getpolar (x!, y!, theta!, radius!)
  'given cartesian coordinates x and y, return polar coordinates theta
  ' in degrees, and radius r
  'note that this function returns theta from 0 through 360 (not usual)
  xx# = x!
  yy# = y!
  rradius# = SQR(xx# * xx# + yy# * yy#)
  IF xx# = 0# THEN 'on vertical axis
    SELECT CASE yy#
      CASE 0#
        ttheta# = 0#
        rradius# = 0#
      CASE IS < 0#
        ttheta# = 270#
      CASE IS > 0#
        ttheta# = 90#
        rradius# = yy#
    END SELECT
  END IF
  IF yy# = 0# THEN 'on horizontal axis
    SELECT CASE xx#
      CASE IS < 0#
        ttheta# = 180#
      CASE IS > 0#
        ttheta# = 0#
        rradius# = xx#
      CASE 0#
        'ignore
    END SELECT
  END IF

  IF xx# > 0# AND yy# > 0# THEN 'upper right
    ratio# = yy# / rradius#
```

```
    sintheta# = ratio#
    tantheta# = sintheta# / SQR(1# - sintheta# * sintheta#)
    thetarad# = ATN(tantheta#)
    ttheta# = thetarad# * 57.2958#
  END IF
  IF xx# < 0# AND yy# > 0# THEN 'upper left
    ratio# = (-1# * xx#) / rradius#
    sintheta# = ratio#
    tantheta# = sintheta# / SQR(1# - sintheta# * sintheta#)
    thetarad# = ATN(tantheta#) 'angle in radians
    ttheta# = 90# + (thetarad# * 57.2958#)
  END IF
  IF xx# > 0# AND yy# < 0# THEN 'lower right
    ratio# = xx# / rradius#
    sintheta# = ratio#
    tantheta# = sintheta# / SQR(1# - sintheta# * sintheta#)
    thetarad# = ATN(tantheta#)
    ttheta# = 270# + thetarad# * 57.2958#
  END IF
  IF xx# < 0# AND yy# < 0# THEN 'lower left
    ratio# = yy# * -1# / rradius#
    sintheta# = ratio#
    tantheta# = sintheta# / SQR(1# - sintheta# * sintheta#)
    thetarad# = ATN(tantheta#)
    ttheta# = 180# + thetarad# * 57.2958#
  END IF
  theta! = ttheta#
  radius! = rradius#
END SUB

SUB GetSeries (Series())
  SHARED raw(), index%, prevx, prevy, prevz, seriesstart%, serieslength%
  'look through array raw starting at point seriesstart%
  'return array series with the next series, less any outliers
  'update seriesstart% and serieslength%
  endfound% = 0
  serieslength% = 0
  DO WHILE seriesstart% < index% AND endfound% = 0
    'examine next point
    nextpoint% = seriesstart% + 1
    lookatx = raw(nextpoint%, 1)
    lookaty = raw(nextpoint%, 2)
```

```
lookatz = raw(nextpoint%, 3)
'is this point at end of the series?
'yes if it differs from previous value by more than resett proportion
crit = prevx * resett
IF ABS(lookatx - prevx) > crit THEN 'it must be beyond this series
 endfound% = 1
ELSE
 'increment general pointer
 seriesstart% = seriesstart% + 1
 'this point is a potential member of this series--if it's not an outlier
 critx = ABS(prevx * sen) 'must differ by more than these amounts to be  "
 crity = ABS(prevy * sen)
 critz = ABS(prevz * sen)
 IF ((ABS(lookatx - prevx) > critx) OR (ABS(lookaty - prevy) > crity) OR
(ABS(lookatz - prevz) > critz)) THEN
 'its an outlier
 ELSE 'its legitimate if its in range,add it
  ok = 1
  IF lookatx < 5 OR lookatx > 25 THEN
   ok = 0
  END IF
  IF lookaty < -10 OR lookaty > 0 THEN
   ok = 0
  END IF
  IF lookatz < 10 OR lookatz > 20 THEN
   ok = 0
  END IF
  IF ok = 1 THEN 'valid
   serieslength% = serieslength% + 1
   Series(serieslength%, 1) = lookatx
   Series(serieslength%, 2) = lookaty
   Series(serieslength%, 3) = lookatz
  '  prevx = lookatx
  '  prevy = lookaty
  '  prevz = lookatz
  END IF
  prevx = lookatx
  prevy = lookaty
  prevz = lookatz

 END IF
END IF
```

```
  LOOP 'go back to look at next value
'at this point, either series is complete, or we ran out of data

END SUB

SUB SortArray (noitems%)
  'sort array Series(noitems%) by values of Series(3), smallest in 1,
  'largest in noitems%
  'uses Shell sort
  SHARED Series()
  nitems = noitems%
  lag = INT(nitems / 2)
  DO WHILE lag >= 1
    DO
      done% = 1
      FOR i% = 1 TO nitems - lag
        IF Series(i%, 3) > Series(i% + lag, 3) THEN
          SWAP Series(i%, 3), Series(i% + lag, 3)
          SWAP Series(i%, 2), Series(i% + lag, 2)
          SWAP Series(i%, 1), Series(i% + lag, 1)
          done% = 0
        END IF
      NEXT i%
    LOOP UNTIL done% = 1
    lag = INT(lag / 2)
  LOOP

END SUB
```