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IEEE 3D BODY PROCESSING INDUSTRY CONNECTIONS

LANDMARKING FOR PRODUCT DEVELOPMENT

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LANDMARKING FOR PRODUCT DEVELOPMENT

ABSTRACT

This paper seeks to explore where current landmarking definitions have difficulty bridging traditional and technological practice. The paper summarizes current definitions in a standard format to encourage discussion toward practice suited for both manual and virtual environments. The goal is toward definitions that enable a specific placement whether that references a point, curve, position. The paper compares methods of traditional manual landmarking in physical space, manual landmarking in virtual space (semi-automated), and automated virtual landmarking, expanding on landmark typologies. Adoption of a standard approach to the definition of the landmarks presents an opportunity to consider how they may be revised for better continuity between physical and virtual environments. This paper provides a platform for multiple users in different fields to find a common understanding of landmarks for further development of technology enabled measuring practice. Efforts toward made-to-measure and increased adoption of 3D technologies heavily rely on clarity of landmark definition to support applications of technology for human measurement. Improved landmarking suitable for wildly varying human morphology may well be the segue for improved adoption of 3D technologies. This paper reinforces the importance of landmarks are the primary drivers for measurements and for explores the links between body and product in a manner that serves the transition toward virtual fitting and technology enabled product development.

1. FOCUS OF THIS REPORT

1.1. GENERAL

The term landmarking in product development refers traditionally to a point or position on the body that specifies the start, end, or placement of a measurement that is then used to inform product development. Landmarks are the key defining points for gaining measurements of the body. Traditionally a landmark would be defined by direct interaction with the body surface to define a point relative to a skeletal feature, a surface feature, or by reference to anatomical features common to a population. The transition to virtual environments and the need to landmark a body based on its 3D surface using semi-automated or automated methods introduces new ways of interacting with the body and new requirements for defining landmarks. The process of landmarking is grounded in manual methods, which are often learned in practice and have few detailed accessible guides for the non-practitioner. It is evident to many currently involved in research and development into human measurement that accessible guidance is difficult to locate. This can lead to issues when developing systems requiring such a broad range of skills. Existing standards, books, and papers aimed at supporting landmark and measurement definitions do not provide sufficient information to ground the varied user base [1], [2].[1]

This report seeks to explore where current definitions have difficulty bridging traditional and technological practice and presents a discussion toward standards suited for both manual and virtual environments using tools linked to body scanning. Discussion builds from an initial IEEE publication [3] and from work connecting body measurement more directly to product development methods [1], [2], [4].

It is hoped that this paper provides a platform for multiple users in different fields to find a common understanding of landmarks for future development in landmarking as we transition to a technology-enabled measuring practice. The principal focus is the need for landmarking to be understood by varied practitioners who, by their backgrounds, will have different understandings of the body, its anatomy, and human measurement in real and virtual environments—experts in human measurement, clothing practitioners, those involved in making body worn products, engineers, and computer scientists. The paper outlines the definition of landmarks to be used to guide the development of 3D tools for automated virtual measurement in computer environments, like body scanning and 3D automated garment design. It is hoped that doing so will provide an opportunity to revise landmark definitions better suited to clothing applications. The paper is not exhaustive and largely focuses on body worn products for the major body regions and only goes into depth for key landmarks where current guidance and knowledge permit. The goal is for this paper to stimulate the comprehensive definition of virtual landmarks tied to the real body to support the advancement of virtual tools for supporting body worn product development.

[1] Numbers in brackets refer to the sources listed in Section 6: References.

1.2. INTENDED REPORT OUTCOMES

This paper addresses the following outcomes:

a) Expanded discussion of landmarks purpose and definition for supporting the identification of points/positions to be used as a basis for human measurement.
b) A focused list of key landmarks suitable for automated or manual methods in both physical and virtual environments, which are central to product development practices.
c) Classification of landmarks by typologies so they can be understood and considered in the different environments in which they are located. Some examples are differences between landmark types such as skeletal landmarks; soft tissue landmarks/surface features; underlying body structure (muscles, fat deposition, links between skin and underlying structure); and related landmarks (those positioned in reference to another landmark, it is possible to consider secondary and tertiary landmarks in a hierarchical system). However, currently there are no broadly recognized typologies for landmarks.
d) A template to support the definition of landmarks that help to create a standard method to recognize key considerations for each of the selected landmarks. Support the manual placement of virtual landmarks. This is important in the case of checking scan data, as well as providing an opportunity to revise landmark definitions to better suit clothing applications.
e) Discussion of the broader considerations for defining landmarks in virtual environments.
f) Recommendations for areas of development to support a better understanding of landmarks across the varied user base. How landmark location can be narrowed by knowledge of body morphology and structure for relevance in both manual and virtual environments and for cross platform collaboration. While there is standardization of measurement procedures, manual landmarking is a learned skill, which does not translate into good guidance for locating points on body scan geometry.

2. EXISTING LITERATURE ON LANDMARKING

Landmarking is used across a range of fields and each field has literature to guide on how landmarking should occur. As a manual process it is however generally accepted that learning how to landmark is done in practice and therefore while definitions may offer differing degrees of description, the actual process of location is expected to be learned through practice. This means there are few sources that actually provide instructive detail on how to locate landmarks. Van Sint Jan [5] provides detailed instruction on how to locate in vivo landmarks, Basmajian [6] outlines surface anatomy, Field [7] provides guidance on landmarking and Palastanga et al. [8] provides some further details on anatomy and landmarks. From a clothing specific perspective consideration of landmarking and measurement for clothing is also outlined by Beazley [9]. Published (not raw) data from English and German children were found in literature in respectively the British Standard 7231 (BSI 1990) and in a DIN33402 (DIN 1981). CAESAR [10] data is often used to check algorithms, but little exists to inform what the landmark is defined by, in terms of placement or geometry.

As well as the previously named sources, there are a number of standards to support human measurement and

the use of technology. However, these standards are often ambiguous on landmark definition, which is central to the precise measurement of the human body. Further, the precise algorithms utilized within measurement extraction software remain undocumented. While understandable, this lack of transparency has contributed to difficulties in the body-to-pattern mapping process. With pattern-making theory being directly related to measurement method, discrepancies in landmarking and measuring are key to successful mapping of body-to-pattern [2], [11]–[13]. Standards to clarify this unavoidable lack of communication (keyed to intellectual property) have become urgent. Indeed, efforts toward made-to-measure and increased adoption of 3D technologies rely on clarity of landmark definition to support applications of technology for human measurement.

In addition to the above, there are efforts by a large variety of independent international standards organizations such as the ASME, the ASTM International, the IEEE, the Internet Engineering Task Force (IETF), SAE International, TAPPI, the World Wide Web Consortium (W3C), and the Universal Postal Union (UPU).

3. LANDMARKING DISCUSSION

Landmarks are used in a variety of fields, but this white paper addresses a landmark as it relates specifically to product and clothing applications and human measurement for the purpose of product development. With regard to product development, landmarks are repeatedly locatable points/positions that are consistently present regardless of age and gender. The difficulty within current practice is that some landmarks are referenced by easily distinguished anatomical point (wrist or ankle bones) while others are referenced as points within an area (waist or crotch). The goal, therefore, is toward definitions that enable a specific placement whether that references a point, curve, position, or area. This section will outline broadly the major typologies of landmarks and introduce those now available in virtual environments.

3.1. WHAT IS A LANDMARK

In terms of this paper, a landmark is defined as a point relative to the surface of a real or scanned surface and could be defined directly from the surface. It is important to retain the distinction between a landmark and the resulting measurement. The placement of landmarks is the first step in human measurement. Measurements are taken between landmarks as either a straight-line distance or distance following body contours. In the field of landmarking for body worn products, (TABLE 1), a landmark can be broadly categorized as follows:

a) A reference used in the defining of a position to take a measurement
    1) A start or end point for a length, width, depth, or circumference.
    2) A location to place a measurement (transverse plane) on or around the body.
    3) A point of specific prominence (e.g., greatest projection, smallest circumference).
    4) A division of a measurement (e.g., quarters, halves).
    5) A point to direct patternmaking for product design (e.g., armscye, waistband).
b) A point used to identify joint centres (e.g., elbow, knee).

c) A point to relate a product to a body, an anchor point (e.g., side neck, crotch point).

d) A point to relate bodies together, a registration point (e.g., side neck, crotch point).

TABLE 1 Summary of landmark use

Landmark usage type	LM usages	Discussion
Segmentation landmarks	Used to divide the body into regions such as front/back and left/right.	Allows for segmentation of the body into regions. Knees and elbows separate the upper and lower regions of the limbs.
Joint center landmarks	Used to define limb junctions/joints and areas where movement causes measurement change.	The placement of joint landmarks (knees, elbows) needs to correlate to both avatar rigging [14] and pattern-making practice for an understanding of movement ease.
Reference landmarks	Determination of circumference division points (left/right and front/back).	Does a better job at mapping the body to product and enables greater understanding of garment pattern shaping requirements.

3.2. CONSIDERATIONS FOR DEFINING MANUAL LANDMARKS

While traditional landmarking and measurement practice can dynamically account for slight changes in posture and pose, virtual practice requires a static pose. This is because highly mobile areas of the body change their appearance and surface presentation with movement such as bending (e.g., arm, torso, neck, leg) [13]. It would be broadly assumed that landmark definitions in virtual environments would relate to bodies captured in the Standing Position A [15], but the hope is that landmarking theory will evolve for application in all poses. Until then, the A pose best presents a baseline for honed mapping practice. The A pose is close to the anatomical position [8], which can be considered as the base posture for discussion of anatomy and movement as used in this paper. Examples of poses are shown in TABLE 2.

Principally a landmark defines a position (usually a point) on a body and relates to a feature of the body, either related to its surface or underlying structure. Landmarks are either defined as core or derived (TABLE 3). For example, a landmark may define the placement of a circumference for the waist (level 1 is the core landmark), when placed, this waist circumference may then be divided into quadrants with positions defined for the center front (CF), center back (CB), and the sides (level 2 derived landmarks). In other words, some landmarks can only be obtained through a sequence of locating other landmarks.

Landmarks are most often identified by their typology, distinct features. In some cases, landmarks are dependent on multiple typologies to define their location (TABLE 4). The typologies of landmarks determine how variable it might be in a population, how it might be influenced by movement, and how easily it may be located across different measuring platforms.

TABLE 2 Body poses for measurements

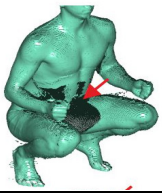
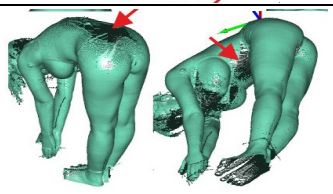
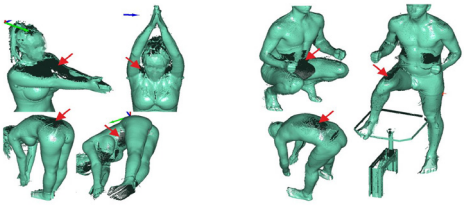
Pose types	Considerations	Images
A pose (standing)—base pose for current apparel applications	Underarm region may have a lot of ghosting, webbing, and/or occlusions; areas where morphology is missing or blended together and therefore indistinguishable.	
T pose (standing)	Shoulder measurements will be impacted.	
A pose (sitting)	Underarm region may have a lot of ghosting/occlusions. Crotch measurements will be impacted.	
T pose (sitting)	Shoulder measurements will be impacted. Crotch measurements will be impacted.	
Squatting (while standing)	Many measurements may have ghosting/occlusions. Leg girths will be affected. © Inga Dāboliņa	
Bending (while standing)	Mid torso region measurements will be impacted. © Inga Dāboliņa	
Dynamic poses	With improved body-to-pattern mapping theory, 4D scanning will permit a better understanding of changes to body morphology during movement. © Inga Dāboliņa	

TABLE 3 Landmarks identified from single typologies

Type	Definition	Examples
Skeletal	The main manual landmark site. A position on the body determined with relation to the underlying skeletal structure.	▪ Lateral Malleolus—Outer ankle bone on the left and right [8] or Medial Malleolus (Inner Ankle) ▪ C7 – 7th Cervical vertebrae—The bony projection of the spine of the 7th vertebrae in the cervical section of the spine [8] ▪ Acromion (shoulder) ▪ Olecranon (elbow) ▪ Mid-patella (knee) ▪ Iliac crest
Soft tissue (muscle)	A point defined on the body surface relative to muscle structure.	▪ Bicep ▪ Calf ▪ Thigh
Soft tissue (adipose tissue)	A point defined on the body surface relative to fat or adipose tissue.	▪ Folds of the waist ▪ Gluteal furrow
Soft tissue (skin surface feature)	A point defined on the body surface relative to a soft tissue feature.	▪ Nipple ▪ Omphalion (belly button) ▪ Eyes
Derived landmark	A landmark defined in relation to another landmark.	▪ Back of the knee level with the mid-patella on the front ▪ Points on any circumference that divide it into arcs, for instance the side waist points on the waist or hip circumference
Largest/Smallest circumference	A landmark defined from a largest or smallest measurement within a region.	▪ Virtual Environments—The hip as a largest circumference is often defined in this way ▪ Manual—The ISAK uses this definition for the calf as the largest circumference ▪ Virtual Environments—The smallest leg circumference proximal to the ankle is defined in this way
Narrowest point	A position on the body that represents the narrowest point in a given plane.	▪ Used as a proxy for the waist
Widest point	A position on the body that represents the widest point in a given plane.	▪ Sometimes used for the hips
Greatest projection	A landmark defined as the greatest projection of the body. Or center of an area of largest projection.	▪ The bust and seat are landmarks commonly defined by these features ▪ Maximum belly circumference ▪ Shoulder blades protrusion
Lowest point	A position on the body that represents the lowest point in a transverse plane.	▪ Sole of feet ▪ Crotch point
Highest point	A position on the body that represents the highest point in a transverse plane.	▪ Vertex of head—This may be impacted by standing position and width between feet ▪ Virtual Environments— this may be impacted by hair; a hair offset may be required to obtain actual height
Product defined	In some instances, a product itself may determine the position the requirements for the position of a landmark.	▪ Waistband ▪ Bra straps ▪ Bra cup shapes ▪ Underwear placement regarding gluteal fold ▪ Raglan vs. set-in sleeve

TABLE 4 Landmarks identified from multiple landmark typologies

Combination landmarks	LM typologies	Discussion
Crotch	Lowest point Soft tissue (underlying fat)	The crotch does not relate to a specific body feature, typically in manual practice it would be defined by the measurement instrument as is evident in the existing guidance [9],[16],[17].
Widest hip	Widest point and/or largest circumference.	Sometimes the widest hip point does not correlate with the largest circumference girth.
Axilla (Armpits)	Left/Right and Front/Back	Discrepancies are frequently reconciled (averaged or the maximum used) for symmetry within the garment.
Neck	Left/Right and Front/Back	The side neck point needs to be reconciled with pattern-making practice (set distance from front/back neck) and unique body morphology.

3.3. CONSIDERATIONS FOR DEFINING VIRTUAL LANDMARKS

In terms of body scanning, the landmark may be defined relative to the point cloud or surface created from data that is filled to compensate for occlusions. It is anticipated that the scanned body would be a closed surface as is commonly available from many body scanning applications, though landmarking may occur on a point cloud depending on the scanner type. While landmarking is grounded in traditional manual methods of measurement, the introduction of methods to capture and analyze the body in virtual environments brings new considerations. The transition to analyzing the body in virtual environments (virtual avatar) brings opportunities as well as complexities and limitations with regard to previous methods of manual human measurements.

To better understand discrepancies between physical and virtual landmarking and measuring, a method for semi-automated measuring was explored using the software Rhino 7/Grasshopper [18]. While the methods utilized may or may not mimic undisclosed proprietary practice, they are useful for understanding where discrepancies between physical and virtual practice will arise. The methods used for the semi-automated landmarking in this paper builds on the previously documented use of slicing loops (curves created by intersection of designated cutting or slicing planes and the body mesh created from the data point cloud of the scan) [19] and feature discriminant functions (curvature calculation) as a method to determine the relative location of the landmark as noted in referenced sources [20].

The following methods were found useful for determining the location of landmark points. These methods are offered for discussion and further examination, not as fully tested methodologies. Their use is mainly to present an understanding of the difficulties faced by those developing measurement extraction software so that improved methods correlated to mapping processes may be considered.

Virtual landmarking methods are as follows:

- Designate measurement zones as a percentage of body height to narrow area of focus.

- Allocate caliper depths and widths on transverse planes to assess body weight distribution.
- Use the Intersection of planes and bounding boxes.
- Use the intersection of x, y, z coordinates to reference points in Cartesian space.
- Consider the inflection points of curves to assess complex morphology.
- Compare the largest/smallest girth within a region.

Since a landmark in a virtual environment exists as a 3D coordinate specified by X, Y or Z (Euclidean space), it is necessary to understand the importance of landmark coordinates. For example, when defining the knee circumference, the first consideration is vertical height to locate a transverse plane for girth assignment relative to manual measuring. Attention to the x and z coordinates, however, offers data regarding stance and posture beyond that which can be reasonably obtained in a physical measuring setting; the joint center of the knee can be defined relative to the lateral, medial, distal, and proximal borders of the patella.

The definition of an origin point, therefore, becomes central to landmark point definitions. Not all body scanning technology uses the same datum or zero point from which to describe the origin for the placement of the body and landmarks. Some scans reference a corner of a bounding box, while others use the head, or crotch point. CAD software is generally divided into either Y or Z defining the vertical axis and with most using the right-hand rule for the relationship of x, y, z, and some software allowing for switching between the two. CAD software that started from a 2D perspective tend to use Y for the vertical axis, while CAD software that started from a 3D perspective (for architecture or ship building), tend to use Z for the vertical axis. For discussion here, y was used for the vertical axis and x for the horizontal axis. This correlates with the common placement of fabric grain on the body; weft grain on the x axis and warp grain on the y axis, and fabric wrapping around the body in the z axis. The orientation of the coordinate system (e.g., x, y, z referenced to front of body and floor), the units of measure (millimeters, centimeters, or inches), and the origin point should be identified in the metadata of the scan so they can be adapted suitable for practice. For the purpose of this paper, the following assumptions were used:

- Units of measure are millimeters (mm) with a level of accuracy being 1 mm.
- The procedure is relevant only to the A pose with the angle of the arms not exceeding 45% from vertical.
- The dimension for height for a person in a standing position will be greater than dimension for width.
- It is assumed the avatar is a true representation of the physical body; webbing, bridging, and holes will have been repaired.
- The scan is oriented with y representing vertical body height, x representing horizontal girths, and z representing body depth.

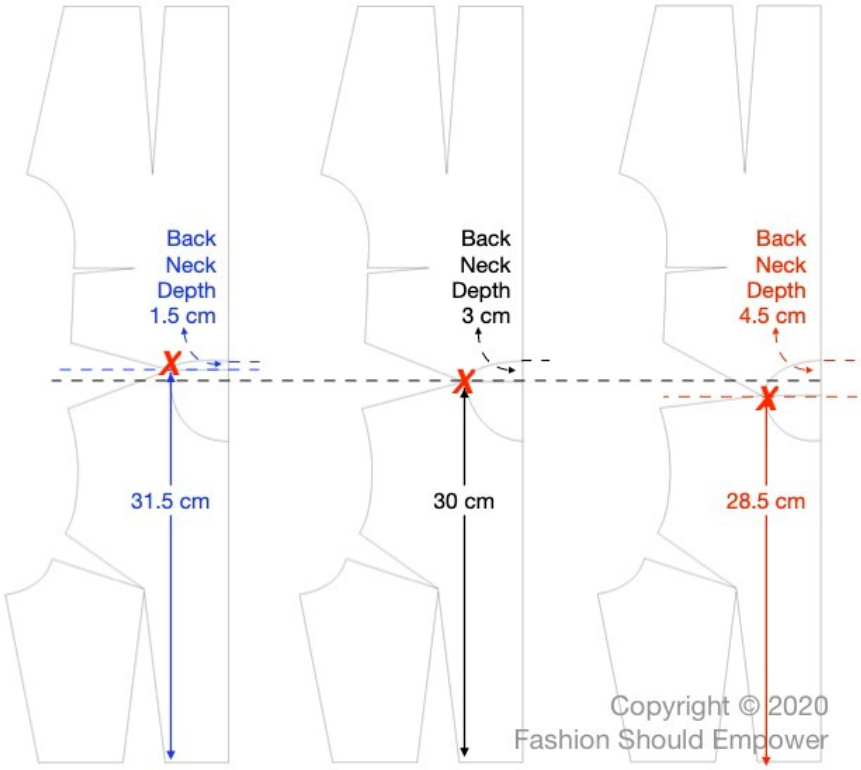
3.4. SEQUENCE OF LANDMARKING

Landmark sequence relates to the order in which landmarks are located (secondary landmarks derived from core landmarks). While not always critical for physical practice, it is vitally important for virtual practice. For example, all landmarks are reference to a base point of origin. From there, landmarks are located in y according to typography. A transverse plane placed at this y location offers a perimeter segment for measuring girth circumferences. If desired, the circumference may be further segmented with divisional derived landmarks. An example of this would be the division of a circumference in a series of arcs, usually front, back, left, and right. In this example, landmarks are derived along a transverse plan (essentially from a measurement), but it may also be

desirable to derive a landmark from one or more other landmarks (e.g., half division between two landmarks, a set distance from a landmark). These sub-divisional landmarks are derived in an ordered sequence following the placement of a core landmark. Such points are important in driving product development making sequencing a critical component of the body to pattern mapping process.

Methods of landmarking and measuring the scanned body have been well documented (as noted in Section 2) but the precise algorithms utilized within measurement extraction software remain proprietary. While understandable, this lack of transparency has contributed to difficulties in the body-to-pattern mapping process. With pattern-making theory being directly related to measurement method, discrepancies in landmarking and measuring are key to successful mapping [2], [13]. Standards to clarify this necessary lack of communication (keyed to intellectual property) have become urgent. As illustrated in FIGURE 1, landmarks are critical for body-to-garment mapping methods. It therefore follows that efforts toward made-to-measure and increased adoption of 3D technologies also rely on landmarks.

FIGURE 1 Side neck landmarks affecting division of front from back regions



3.5. LANDMARKING OF BODY REGIONS

Body Regions are important for the translation of 3D body-shape to 2D patterns. For anthropometric assessment, the body is segmented into regions to differentiate the torso from limbs and head. These regions are further sub-divided to identify key joint locations. Regional landmarks have a degree of flexibility in that the perimeter

boundaries (seams on a garment pattern and split lines on a 3D object) can be slightly relocated forward/backward or left/right (TABLE 5). The waist may also have multiple methods and locations for the appropriate measurements as needed for garment pattern (TABLE 5). It should be noted that while garment seams provide a fitting device for controlling fabric and shaping fabric to body morphology [21], they are not necessary. However, garments without seams will have more ease, or fit error if ease is not desired (e.g., t-shirt without a side-seam vs. one with). FIGURE 3 illustrates how variations in landmarking placement directly impact body-to-pattern mapping of a traditional side-seam.

Regions relate to apparel pattern-making blocks and also reflect regional divisional lines making it possible to flatten a non-developable 3D object (body) to a developable 2D object (body-block garment pattern). FIGURE 2 illustrates the use of landmarks for regional body segmentation and the proper transformation of a 3D body mesh to a 2D body-block garment pattern. In this example, the torso has been segmented into front and back torso and legs. By using landmarks directly for the correct placement of the splines (Nurbs) on the body, the unique mathematical flattening of a given 3D body to 2D form can be achieved.

FIGURE 2 Regional landmarks affect the placement of split lines for scanned body mesh flattening

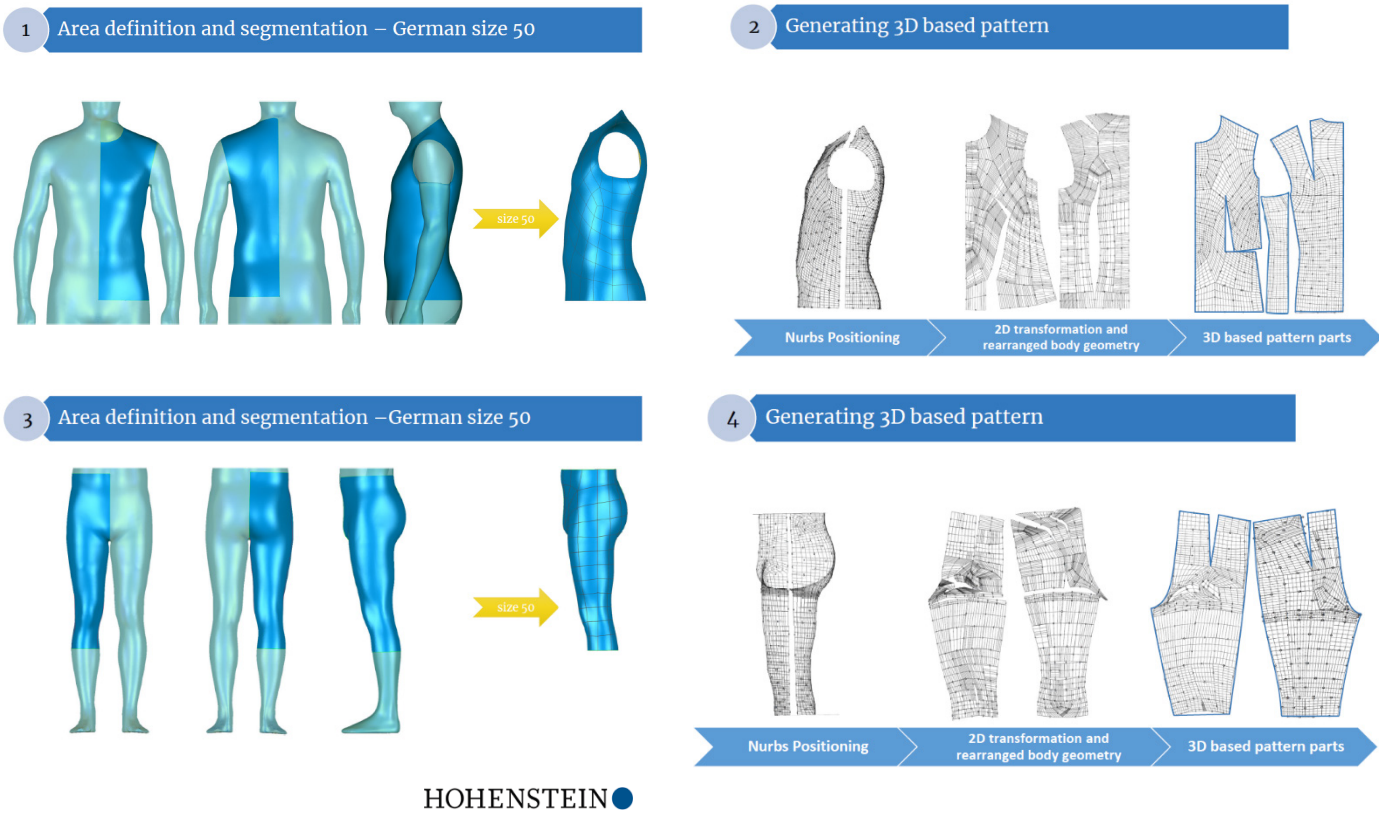


FIGURE 3 details possible landmark definitions that could be utilized to define patch perimeter boundaries and split lines for segmenting the 3D object (body). Current landmarking protocols utilize the flexibility of regional landmark placement illustrated in FIGURE 3 but landmark definitions to better guide this process would support further body-to-pattern study regarding fit preference and movement ease. Study toward side-seam location offers direction toward these better definitions [22], [23].

FIGURE 3 Regional landmarks affecting mapping of body dimensions to pattern

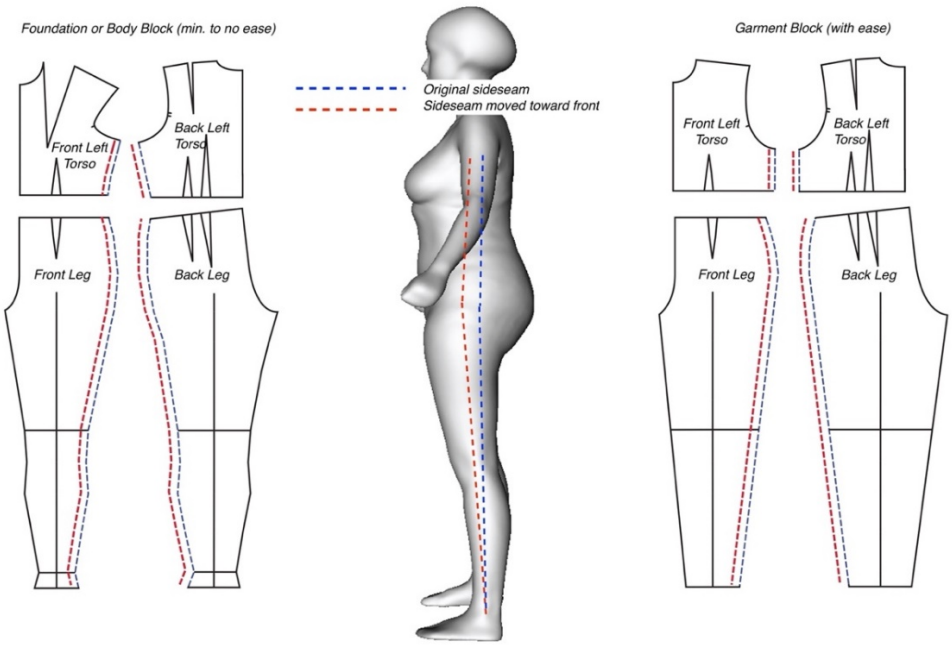


TABLE 5 Example of regional landmarks with 2D to 3D correlation (e.g., mesh split-lines, body-block patterns)

Body region	Sequence	LM point ref.	Landmark name *(left/ right = L/R)*	Manual technique utilized for estimating mesh split line landmarks
Neck and head region	1	**4.21**	Side Neck L/R	25% of the caliper depth of the neck between the back and front neck points (z), the widest point of the neck (x), and the inflection point of the curve coming off the lower neck and the shoulder area (y).
	2	**4.19**	Front Neck	Midpoint of the valley between the clavicles.
	3	**4.20**	Back Neck	Inflection point of the curve coming off the lower neck and the upper back.
Arm region	4	**4.18**	Shoulder L/R	Inflection point of the curve coming off the mid-point of the arm and the top of the torso.
	5	**4.15**	Armscye Front L/R	Inflection point of the curve coming off the arm and chest region on the front of the body.
	6	**4.16**	Armscye Back L/R	Inflection point of the curve coming off the arm and chest

Body region	Sequence	LM point ref.	Landmark name *(left/ right = L/R)*	Manual technique utilized for estimating mesh split line landmarks
				region on the back of the body.
	7	**4.17**	Underarm L/R	Averaged heights of the front and back armscye points (y), mid caliper thickness of the arm (z), and the widest point of the torso (x).
	8	**4.23**	Elbow L/R	Apex of a curve at mid arm.
	9	**4.22**	L/R Biceps	Largest girth between the underarm and elbow.
	10	**4.24**	Wrist L/R	Smallest girth below the elbow.
Leg region	11	**4.5**	Crotch Point	Midpoint between legs (x), lowest point of torso between legs (y), mid caliper thickness of thighs between legs (z)
	12	**4.4**	Knee L/R	Inflection point of two curves on the back of mid leg.
	13	**4.2**	Ankle L/R	Smallest girth above the floor and below the calf.
	14	**4.3**	Calf L/R	Largest girth between the knee and ankle.
Sub-divisional torso region landmarks	15	**4.14**	Bust Point L/R	Midpoint of the domed mound on the front of the body below the Armscye points.
	16	**4.9 – 4.12 or other**	Waist	A waist location between ribcage and the iliac at 62.5% percent of the height between the crotch and underarm.
	17	**4.8**	Hips Seat	25% height between crotch and underarm points
	18	**4.7**	Hips Widest	12.5% height between crotch and underarm points
	19	NA	Center Front Waist	Center front waist placed at mid caliper.
	20	NA	Center Back Waist	Center back waist placed at mid caliper.
	21	NA	Side Waist L/R	Mid caliper width of torso aligned with waist landmark.
	22	NA	Side Hip L/R	Mid caliper width of torso aligned with hip landmark.
	23	NA	Side crotch L/R	Mid caliper width of leg aligned with crotch landmark.
	24	NA	Side knee L/R	Mid caliper width of leg aligned with crotch landmark.
	25	NA	Side Ankle L/R	Mid caliper width of leg aligned with crotch landmark.

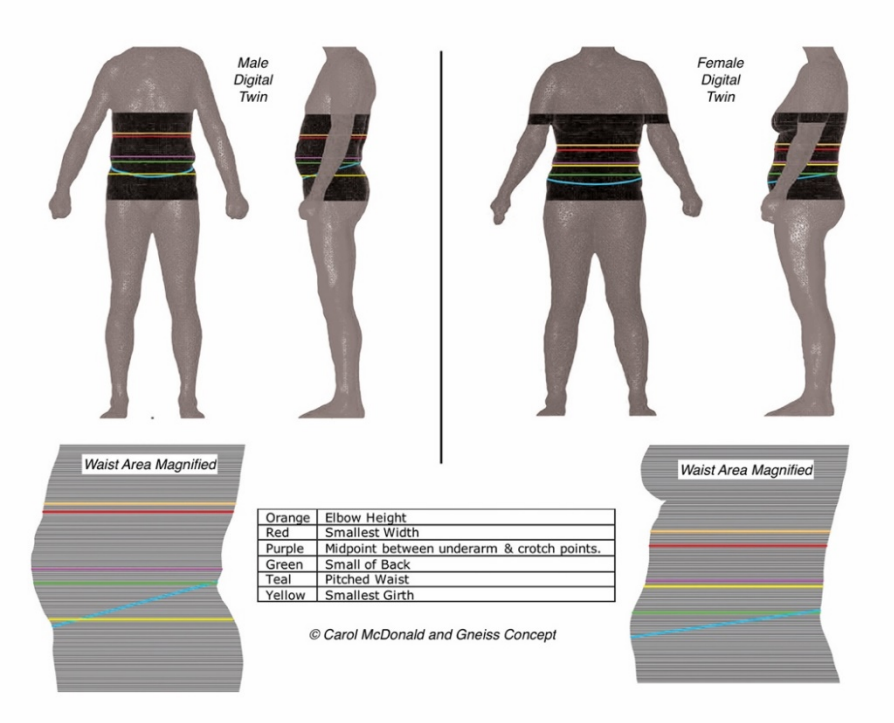
3.6. SUBDIVISION OF BODY REGIONS

Adding further complexity to landmarking is the necessity for further sub-division of body regions. For example, the bust, waist, and hip are critical regional sub-division points. These landmarks direct the acquisition of key girths upon which garment sizing is based yet continue to draw controversy. Some practitioners focus on theory suited to product specific development; others focus on defining an aesthetically pleasing smallest girth, others aim for an anthropometric definition, while still others take a whole-body approach [24]. The hip region garners similar controversy [25]. While each method serves a distinct and warranted purpose, confusion exists as to how to best identify a waist, and hip relevant to garment sizing. Apparel practitioners can ‘agree to disagree’ on ‘best’ method but an offering to the public at large must have a consensus supported by standards. Further, and as illustrated in FIGURE 4, the opportunity for landmarks to improve our body-to-garment understanding is tremendous. Is it reasonable to expect an understanding from non-experts that a high-waisted size 8 pant will have a band girth of 65 cm while a low-waisted size 8 pant band will measure 75 cm? Is it better to reference an anthropometric waist girth linked to skeletal structure and sizing rather than product? Is it possible to define waist and hip relatable to both health and fitness and apparel sizing?

FIGURE 4 illustrates varied locations for sub-division of the mid-torso waist region. The traditional definition of the waist identifies it as point centered on the area between the iliac and lowest rib [26], [27]. Since body weight and fat distribution frequently make the locating of these bony reference points difficult, this definition presents challenges leading to error. The problem is further exacerbated by product-specific definitions requiring the smallest width or smallest circumference of the torso. Analysis indicates that the shape of the female torso might place the smallest circumference onto the base of the ribcage, which is in wear not the waist [27]. Still further analysis supports the need for a pitched waist matching body morphology [24].

FIGURE 4 details six methods for semi-automated landmarking of the waist area. Each of these definitions identifies unique morphology suggesting that the waist area requires more than a single dimension to achieve adequate body-to-pattern mapping. Where a single anatomical waist landmark is limiting, multiple landmarks can better detail unique morphology (mapping). The use of multiple landmarks could present data better able to address individual fit preference concerns.

FIGURE 4 Waist landmark methods for horizontal/angled sub-division

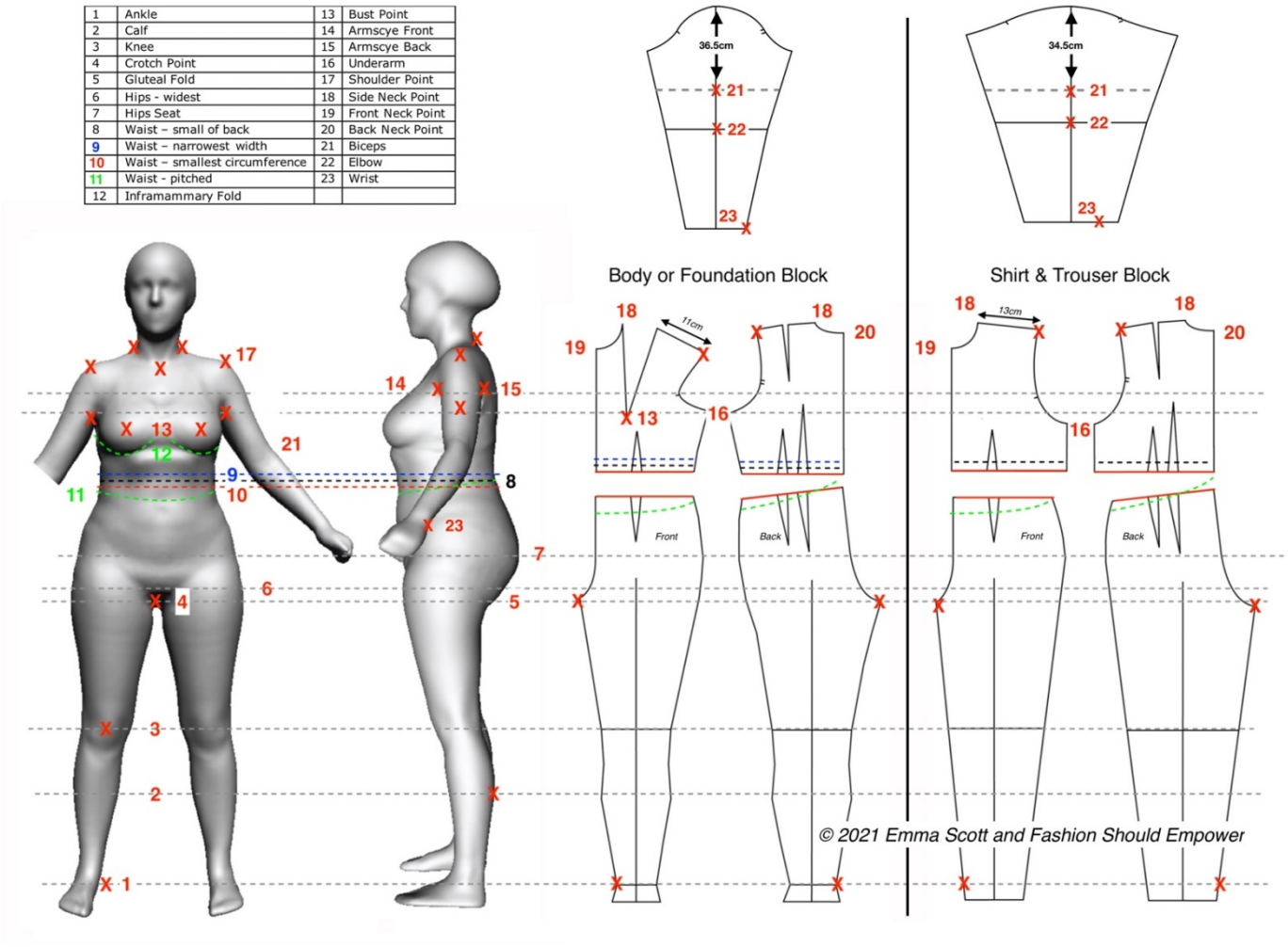


4. LANDMARKING DEFINITION TABLES

This section provides a discussion of key landmarks and seeks to address their definitions as well as the varied considerations for using them in product development. All definitions will refer to the body in the anatomical position (A-pose), using terminology traditionally grounded in human anatomy. The purpose is to provide guidance for expanding landmark definitions for compatibility of use across various disciplines such as manual palpation, semi-automated placement in a virtual environment, or fully automation placement in a virtual environment. Discussion of landmarks is in order of floor to head and from shoulders to hand.

FIGURE 5 provides a visual illustration of the body-to-garment landmark relationship. Landmarks are identified on both fitted (body or foundation block) and non-fitted (shirt and trouser block) garment patterns. Note how pattern landmark position differs from the fitted to non-fitted garment patterns. The moving of critical perimeter landmarks is inherent in garment design, but it also contributes to errors in fit assessment. For example, the illustrated shirt pattern has had the shoulder landmark extended; depending on fit preference, this could be considered a fitting error or a pleasing design feature. Recording the movement of critical perimeter landmarks in digital tech packs will be essential as the apparel industry moves toward improved landmarking and enhanced digital fit assessments.

FIGURE 5 Landmark summary

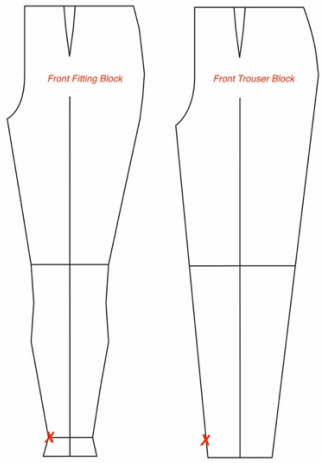


4.1. EXAMPLE OF LANDMARK ANALYSIS TABLE

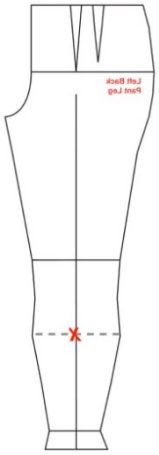
A tabular format inspired by Van Sint Jan [28] has been adopted to summarize landmarking details. Automated landmark descriptions are given with permission of Size Stream [29]. Landmark or Measurement number is noted in the Size Stream document. Images for LM Body Image are provided by Simeon Gill, Emma Scott, Hohenstein or Size Stream unless otherwise noted. Images for LM Pattern Image are provided by Emma Scott.

<table>
<tr><td>Landmark name:</td><td>The common name for the landmark</td><td>LM body image:</td></tr>
<tr><td>Pose:</td><td>Person’s pose</td><td rowspan="5">[Visual of the landmark on the body and/or the scanned body]</td></tr>
<tr><td>Typology:</td><td>The typology of the landmark</td></tr>
<tr><td>Description:</td><td>Type of landmark</td></tr>
<tr><td>Landmark location:</td><td>Occurs on Left and Right or Midline</td></tr>
<tr><td>Measurements using landmark:</td><td>List of key measurements that reference this landmark.</td></tr>
<tr><td>LM purpose:</td><td>This describes the need for the landmark and how its data is applied.</td><td>LM pattern image:</td></tr>
<tr><td>Features to narrow location:</td><td>Details of other features of the body that will narrow the location and help to be certain the LM is correctly identified.</td><td rowspan="4">[Visual linking the landmark directly into the pattern]</td></tr>
<tr><td>Description:</td><td>Description of the landmark.</td></tr>
<tr><td>Discussion:</td><td>Notes on the landmark, including observations and considerations.</td></tr>
<tr><td>Automated location:</td><td>Description of location in a virtual environment.</td></tr>
<tr><td>Sequence for semi-automated virtual landmarking:</td><td colspan="2">How to locate using semi-automated methods in a virtual environment (using height first).</td></tr>
</table>

4.2. ANKLE—INNER

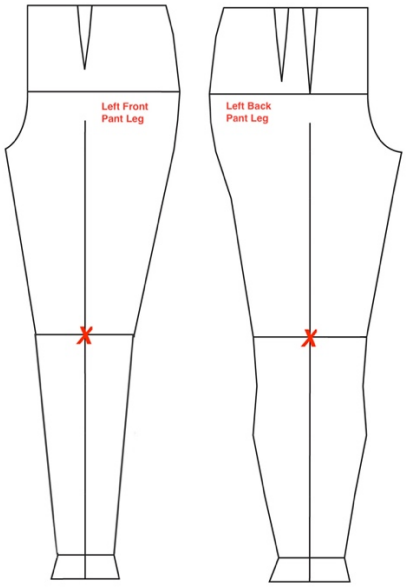
Landmark name:	Inner Ankle/Medial Malleolus		**LM body image:**
Pose:	Standing		
Typology:	Skeletal		
Description:	The ankle point is the middle point of the Malleolus. Medial is at the lower extremity of the Tibia. It is most prominent on the inner side of the ankle and is easily defined by palpation [30].		
Landmark location:	Left and Right		
Measurements using landmark:			
LM purpose:	Measurement Segmentation Defines a repeatable ankle level that can be used to define leg lengths in a pattern.		**LM pattern image:**
Features to narrow location:	Palpate the protrusion of the medial malleolus (inner ankle) to determine the most superior aspect of this process. Junction of foot to leg, based on change in direction of curve tangent of leg and foot curve.		
Discussion:	The ankle provides a consistently locatable point for taking a measurement of the lower leg, though it is not as small a circumference as the smallest lower leg measurements, which is in the narrower section above the ankle and below the sections of the calf muscles.		
Automated location:	The centered right (or left) point of the left (or right) ankle circumference. (Landmarks 92, 95)		
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: within 1% to 9% of total height, slicing curves at every 1 mm of height for each leg.	
	2nd -X	Ridge curve as seen in the front view, over joint for each leg, then max left X for right leg, and max right X for left leg within a narrowed height range to each ridge curve of foot to ankle junction as seen from side view.	
	3rd -Z	Software function of point.	

4.3. CALF

Landmark name:	Calf	**LM body image:**
Pose:	Standing	
Typology:	Largest circumference	
Description:	The largest circumference of the lower leg (shank) occurring due to the muscles of the lower leg in the upper portion of the region between the smallest lower leg circumference and the under-knee point. ISO 8559:1989(en): 2.1.22 maximum girth of the calf measured [26]. The point on the most medial aspect of the calf at the level of the maximal girth), perpendicular to its long axis [31] p. 44.	
Landmark location:	Left and Right	
Measurements using landmark:	Calf circumference, calf height, knee, ankle, medial calf skinfold site.	
LM purpose:	Defines a measurement used in product development of the lower body.	**LM pattern image:**
Features to narrow location:	Using a metal tape measure visually locate the largest position of the lower leg and manipulate the tape measure to locate the largest circumference of the calf [31]. Intersection of the horizontal slicing planes at the max circumference determined in the lower leg region.	
Discussion:		
Automated location:	Maximum contour horizontal circumference of the leg above the ankle and below the knee. (Measurements 54, 55)	

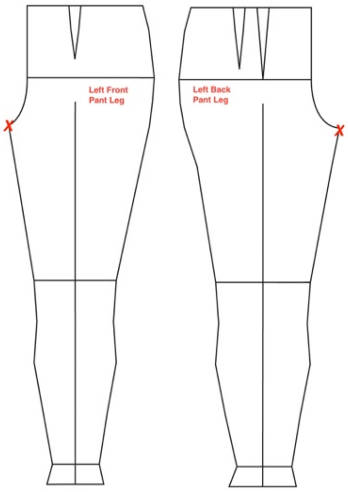
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: within 10% to 30% of total height. The circumference is found first, which then allows the point to be found in this body scanner. Generate a ridge curve of each leg and determine the back of knee starting height by curve of calf. Find max circumference below knee at every slicing curve taken at every 1 mm height. Software function for Y height given at max circumference.
	2nd -X	Automated software function for caliper mid points.
	3rd -Z	Automated software function for caliper mid points.

4.4. KNEE—MID PATELLA

Landmark name:	Knee point/Mid-patella	**LM body image:**
Pose:	Standing	
Typology:	Skeletal	
Description:	Patellare: The midpoint of the posterior superior border of the patella, while the participant is seated with knee flexed to 90 degrees [31] p. 72. Tibiale laterale: The most superior point on the lateral border of the tibial plateau [31] p. 70. Tibiale mediale: The most superior point on the medial border of the tibial plateau [31] p. 74.	
Landmark location:	Left and Right	
Measurements using landmark:	Knee Girth, Knee Height	
LM purpose:	Joint Zone, Critical reference point for garment design.	**LM pattern image:**
Features to narrow location:	Look for indentation change as the tendon pulls over the base of the kneecap to attach to the lower leg.	
Discussion:	Large bodies may have bridging at the knees requiring legs to be split into right and left sides.	
Automated location:	The centered front point of the Right (Left) knee circumference. (Landmarks 65, 69)	

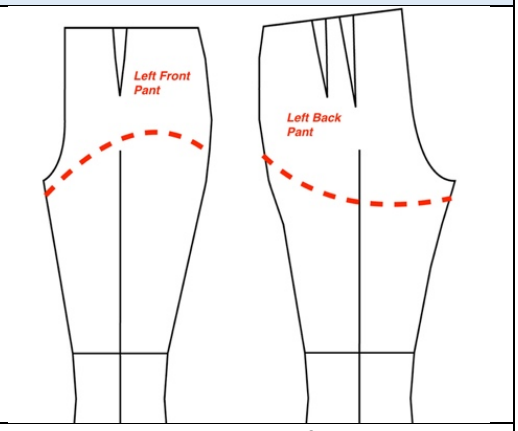
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: within 20% to 40% of total height. Generate a ridge curve of each leg and determine the back of knee starting height by curve of calf. Determine ridge curve of front of knee from knee starting height and upward over knee height every 1 mm in height within a specified.
	2nd -X	Front edge of bounding box of each slicing curve to determine X measurement for each leg.
	3rd -Z	Front edge of bounding box of each slicing curve to determine Z measurement for each leg.

4.5. CROTCH POINT

Landmark name:	Crotch Point	**LM body image:**
Pose:	Standing	
Typology:	Skeletal	
Description:	Lowest point of the torso on the midsagittal plane with the virtual human body.	
Landmark location:	Midline	
Measurements using landmark:	Inseam, Crotch Height, Crotch Length (full, Fr & Bk).	
LM purpose:	Aids depth assessment for drafts of bifurcated (two legged) patterns and also provides a means to separate the back and front parts of a trouser/pant pattern. Segmentation of torso from legs.	**LM pattern image:**
Features to narrow location:	In the Vertical axis (often Y or Z) direction this point is the lowest aspect of the torso Central to the legs in the x direction. The curve of the front pubis and the gluteal fold provide direction for the final crotch point. Extracted crotch curve in sectional views helps to define placement.	
Discussion:	Not well defined in the Y or Z direction. There may be parts of the body connected to the torso, which sit lower than the crotch point (testes).	
Automated location:	Lowest point where thighs meet the pubis bone and zero point. (Landmarks 0)	

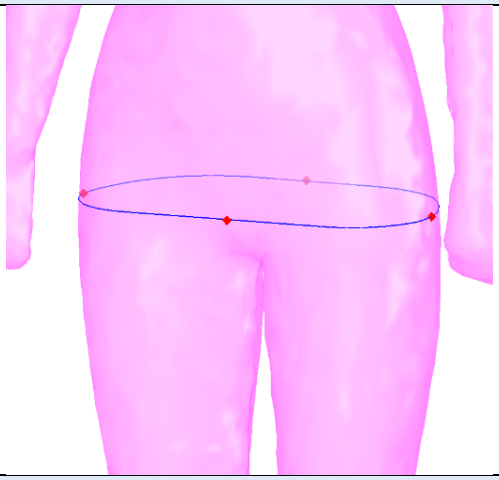
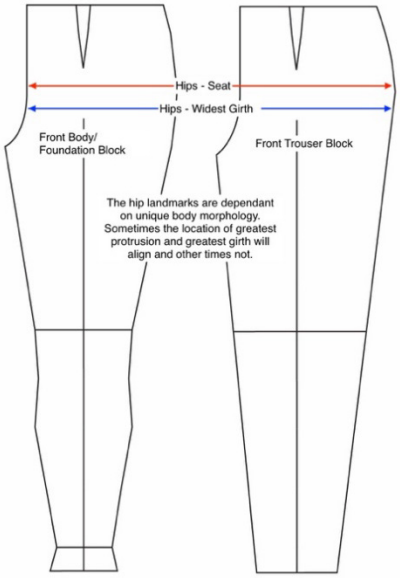
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 40% to 60% of total height of body only, start with 30% to 60% of height and narrow down. Iterative process taking sagittal slicing curves over 40% to 60% of total width along with 1 mm horizontal slicing curves will determine the lowest lines of the torso, either in the front of the body or the gluteal fold. If using the crotch point as the basis for x, z origin point, use the lowest height.
	2nd -X	After determining height of crotch, either at the front of body only or the taking into consideration the height of the gluteal fold, the x value will be used as the x value of the crotch. The x value is centered between the legs.
	3rd -Z	Use a sectional slice at this x to find the z value. The depth will be either at the front curve of the pubis or the center point of the caliper thickness of the legs taken at the gluteal height.

4.6. GLUTEAL FOLD

Landmark name:	Gluteal Fold/sub-gluteal/infra-gluteal/ lower gluteal/inferior buttock/gluteal furrow/gluteal crease/gluteal sulcus	**LM body image:**
Pose:	Standing	
Typology	Soft tissue	
Description:	The crease formed on the posterior aspect of the body at the junction of the inferior part of the gluteus and the superior part of the thigh [31] p. 45.	
Landmark location:	Midline	
Measurements using landmark:	Product-specific landmarks related to the measurement of design lines such as the leg opening of underwear and swimwear.	
LM purpose:	Directly related to product design of garments such as underwear and swimwear.	**LM pattern image:**
Features to narrow location:	The curve of the gluteal where the buttocks meet the posterior aspect of the upper leg. Skin furrow occurring between the base of the buttocks and the posterior upper thigh. There is one on each buttock. Crease of the skin at center thigh that becomes less defined toward the side of the body.	
Discussion:	"This crease does not reflect the lower margin of the gluteus major muscle." [32]	
Automated location:	Not mentioned	

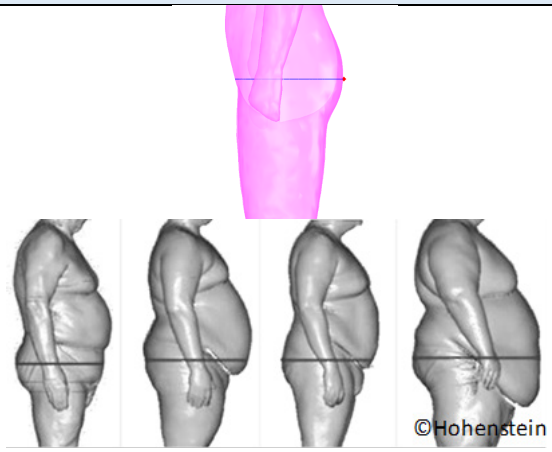
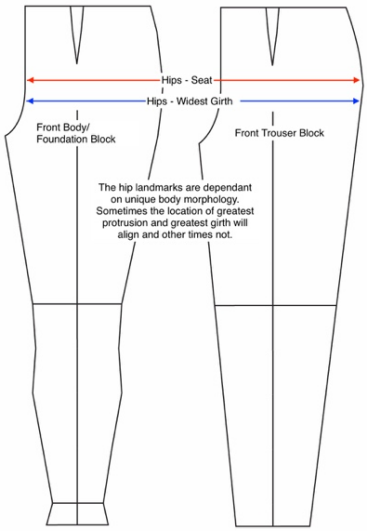
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 40% to 60% of total height of body only, start with 30% to 60% of height and narrow down. Height of gluteal fold may or may not be the same as crotch height front. The height of the gluteal fold will be determined by the change of the curvature between the legs and the buttocks at the midplane of each buttock if asymmetrical.
	2nd -X	Use the same final x value as determined by crotch point front if buttocks are closely symmetrical.
	3rd -Z	The depth will be the either at the back curve ending of the gluteal fold or the center point of the caliper thickness of the legs taken at the gluteal height.

4.7. HIPS—WIDEST

Landmark name:	Hips	**LM body image:**
Pose:	Standing	
Typology:	Largest Circumference/Skeletal	
Description:	Trochanterion: The most superior point on the greater trochanter of the femur—not the most lateral point [31] p. 69.	
Landmark location:	Left and Right	
Measurements using landmark:		
LM purpose:		**LM pattern image:**
Features to narrow location:	Trochanter Looking below the seat and above the crotch the largest lower body circumference above the crotch and below the seat	
Discussion:	Will be impacted by the posture of the scan. As a measurement, the hip is influenced significantly by levels of body fat and clear consideration must be given to this.	
Automated location:	(Called Low Hip) Maximum horizontal circumference between the crotch and left point of OPT Small of back. (Measurements 151)	

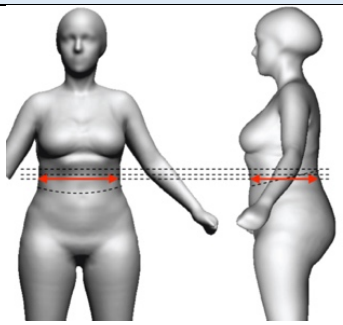
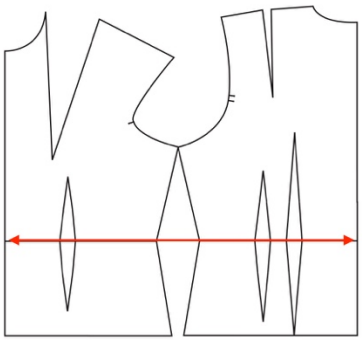
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 40% to 50% of total height of body only, start with 30% to 60%. Determine max absolute z value at the intersection with back edge of bounding box for max buttocks height with slicing curves at every 1 mm of height. Between gluteal height and buttocks height, every mm height, determine the max circumference. If body is twisted in z direction, divide body sliding curves with x center slicing curve to determine quarter points. If body is asymmetrical in x direction, sloped planes may be necessary. Software function for y height given at max circumference.
	2nd -X	Software function for caliper mid points.
	3rd -Z	Software function for caliper mid points.

4.8. HIPS—SEAT

Landmark name	Seat—Buttock projection	**LM body image:**
Pose:	Standing	
Typology:	Greatest Projection	
Description:	The most posterior point, or center of the most posterior area of the buttocks. This point is often compounded with the hip and used to define that measurement, where it may actually be higher [33].	
Landmark location:	Left and Right	
Measurements using landmark:	Hip depth, hip girth	
LM purpose:	Allows the placement of a seat measurements, also helps with understanding shaping requirements for darts in the back of pants/trousers.	**LM pattern image:**
Features to narrow location:	Above the crotch point, below the small of back.	
Discussion:	The curved nature of the shape of the buttocks means there may be a flat region at the greatest projection. The seat will then be the point in the middle of the area of greatest projection. Can also identify girth on front of the body.	
Automated location:	The centered back point of the seat circumference. (Landmarks 46) Seat is the horizontal contour circumference at the most prominent rear point between the horizontal waist height and the crotch landmark height. (Measurements 35)	

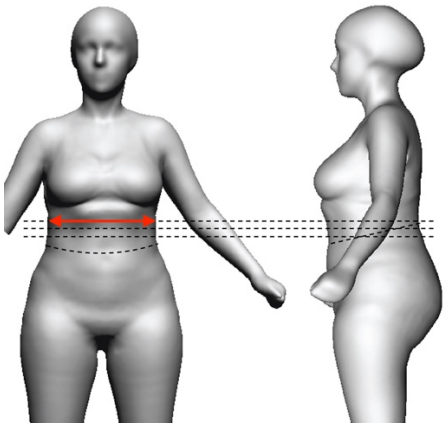
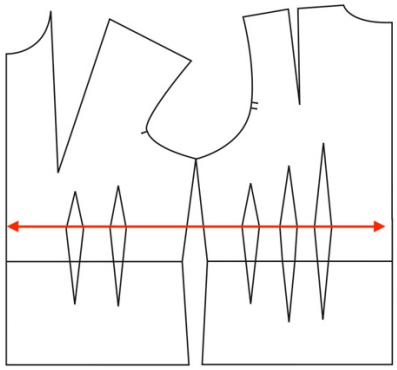
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 40% to 60% of total height of body only, start with 30% to 60%. Determine max absolute z value at the intersection with back edge of bounding box for max buttocks height with slicing curves at every 1 mm of height. If body is twisted in z direction, divide body sliding curves with x center slicing curve to determine quarter points. If body is asymmetrical in x direction, sloped planes may be necessary. Software function for y height at max z.
	2nd -X	Software function for caliper mid points.
	3rd- Z	Software function for caliper mid points.

4.9. WAIST—SMALL OF THE BACK

Landmark name:	Small of Back	**LM body image:**
Pose:	Standing	
Typology:		
Description:	The indentation at the base of the back where the spine is lightly covered by body fat and muscle. The indentation is where the spine changes angle and where the sacral and lumbar spines intersect. The muscles of the lower back help to define this.	
Landmark Location:	Midline.	
Measurements using landmark:	Waist depth, waist girth, rise, pitched waist.	
LM purpose:	A base point from which the waist girth may be refined.	**LM pattern image:**
Features to narrow location:	Deepest point of the spinal curve at the tangential change, closer to the buttocks.	
Discussion:	This has been defined as both the third lumber vertebrae (L3) and the "small of the back." However, if the adipose tissues form a thickening in this area, the small of the back may be above or below the L3 level. This may impact the final waist location.	
Automated location:	The point along the spine, on the surface of the body, where the back intersects the seat. (Landmarks 134)	

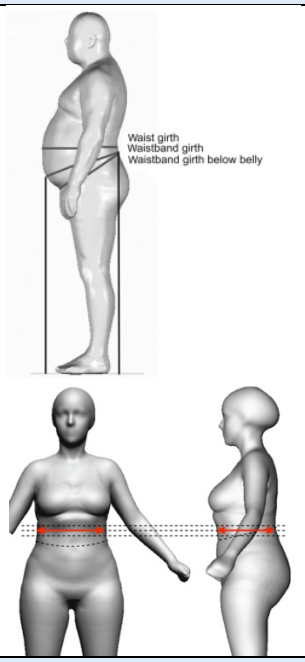
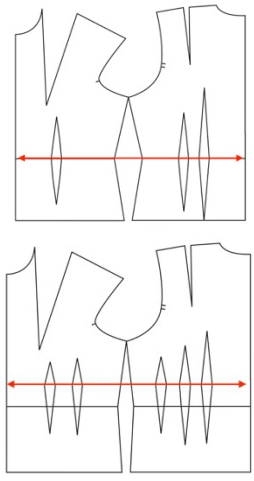
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 50% to 70% of total height and body only. For each curve, at the center of back side of bounding box, take the average X of these points and form an X slicing curve within 40% to 60% of total width. Where the intersection points slope of curve change to vertical, this will be the height zone for the small of back.
	2nd -X	Sagittal slicing curves over 40% to 60% of total width.
	3rd -Z	Software function for z value.

4.10. WAIST—NARROWEST WIDTH

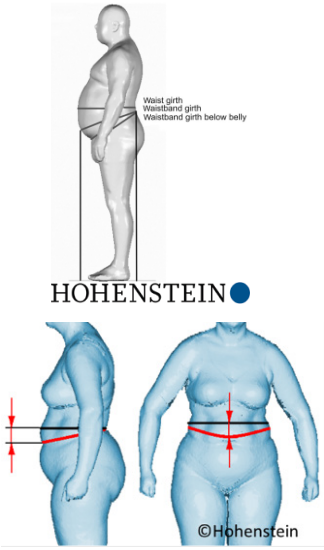
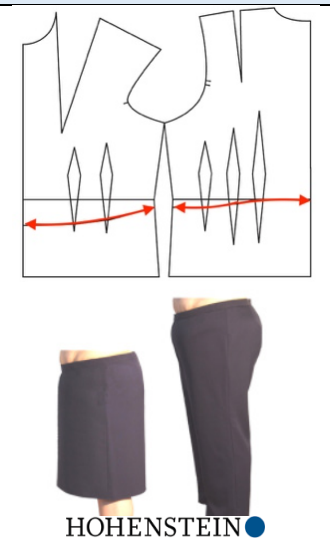
Landmark name:	Waist—Narrowest Width	**LM body image:**
Pose:		
Typology:	Narrowest Point	
Description:	Most concave point of side waist (right) waist when viewed from the front with the virtual human in a virtual standing position as defined in ISO 18825-1, 2.2.1.2 [34].	
Landmark location:		
Measurements using landmark:	Waist Depth Rise	
LM purpose:	Shaping of apparel products at the waist area. Location for top of lower body garments (waistband).	**LM pattern image:**
Features to narrow location:	Within midriff area, below the bust.	
Discussion:	Strongly defined by weight distribution and unique morphology of the ribcage. Narrowest waist and most concave point on the body side frequently conflict. Consideration should be given to setting limits to remain within the defined waist region.	
Automated location:	Horizontal contour circumference taken at the narrowest torso width between the chest and hips when viewed from the front. Sometimes called narrow waist. (Measurements 26, 79)	

Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 50% to 70% of total height and body only. Using slicing curves at every 1 mm of height, find the slicing curve with the narrowest x width. If body is twisted in z direction, the projection to determine the smallest width will need to be perpendicular to the twist. Software function for y height at narrowest x.
	2nd - X	Software function for caliper mid points.
	3rd - Z	Software function for caliper mid points.

4.11. WAIST—SMALLEST CIRCUMFERENCE

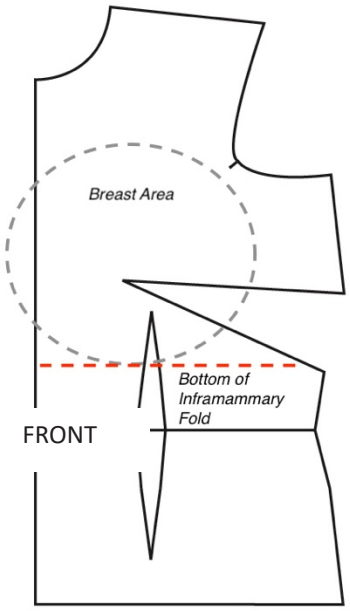
<table>
<tr><td>Landmark name:</td><td colspan="2">Natural Waist Smallest Circumference</td><td>LM body image:</td></tr>
<tr><td>Pose:</td><td colspan="2">Standing</td><td rowspan="4"> 
</td></tr>
<tr><td>Typology:</td><td colspan="2">Smallest Circumference</td></tr>
<tr><td>Description:</td><td colspan="2">The girth of the abdomen at its narrowest point between the lower costal (10th rib) border and the top of the iliac crest, perpendicular to the long axis of the trunk [31] p. 110.
As above with the subject breathing normally and standing upright with the abdomen relaxed as defined in ISO 8559-1, 2.1.11 [26].
Girth between the lowest rib and hip per ASTM D5219-15 [35].
As above at the side of the body per ISO 8559-1, 3.1.22 [26].</td></tr>
<tr><td>Landmark location:</td><td colspan="2"></td></tr>
<tr><td>Measurements using landmark:</td><td colspan="2">Rise, length measurements referencing shoulder, waist height, distance waist to hip, side seam</td><td rowspan="2"></td></tr>
<tr><td>LM purpose:</td><td colspan="2">Product Design—Shaping of apparel products at the waist area.</td><td>LM pattern image:</td></tr>
<tr><td>Features to narrow location:</td><td colspan="2">Palpable skeletal points on the ribcage and iliac.</td><td rowspan="3">  </td></tr>
<tr><td>Discussion:</td><td colspan="2">The “smallest” waist is frequently found relative to morphology, deviating from anthropometric definition.
▪ Sometimes it is found at an angled pitch.
▪ Sometimes it is above the bottom of the ribcage.
▪ With plus sizes, it is frequently measured underneath the belly.
This circumference is important when seeking to shape a garment, as suppression fits a garment form larger to smaller areas.</td></tr>
<tr><td>Automated location:</td><td colspan="2">Horizontal contour circumference of the torso taken at elbow height. (Measurements 28)</td></tr>
<tr><td rowspan="3">Sequence for semi-automated virtual landmarking:</td><td>1st -Y</td><td colspan="2">Range: 50% to 70% of total height and body only. Using slicing curves at every 1 mm of height, find the one with the smallest circumference. Software function for y height at smallest circumference. This may find a mid-rib or under bust circumference and should be compared to the other techniques. May want to compare value with pitched waist value.</td></tr>
<tr><td>2nd -X</td><td colspan="2">Software function for caliper mid points.</td></tr>
<tr><td>3rd -Z</td><td colspan="2">Software function for caliper mid points.</td></tr>
</table>

4.12. WAIST—PITCHED

Landmark name:	Waist—pitched	**LM body image:**
Pose:	Standing	
Typology:		
Description:	Waist placement directed by the small of the back and pitched to suit body morphology and/or product design. The waist level is determined by the deepest part of the spinal curve or at the tangential change, closer to the buttocks. (Hohenstein)	
Landmark location:		
Measurements using landmark:	Rise, length measurements referencing shoulder, Waist height, distance waist to hip, side seam.	
LM Purpose	Product Design—Shaping of apparel products at the waist area.	**LM pattern image:**
Features to narrow location:		
Discussion:	For plus sizes a pitched waist is frequently better suited to morphology. On some figures a pitched waist (measured underneath the belly) may be the smallest waist circumference.	
Automated location:	A circumference taken at an angle from horizontal starting at the back point that is 80% of the distance from the Crotch level to the Small of Back point. The angle can be configured 0–20 degrees. (Measurements 22)	

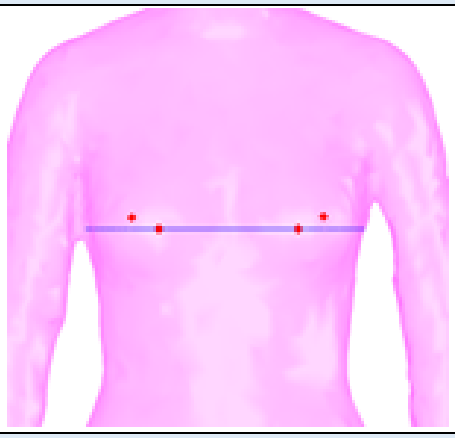
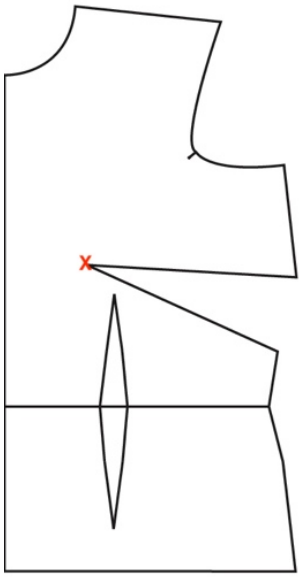
Sequence for semi-automated virtual landmarking	**1st -Y**	Range: 50% to 70% of total height and body only. Using the small of the back as the starting point, 1) take the waist measurement on the horizontal plane for reference and 2) set up a plane to pivot at the small of the back point in both sagittal and transverse planes. The sagittal pivot may be necessary if the hips and buttocks were not symmetrical. Find the circumference of the intersection of plane and mesh. May want to compare value with smallest circumference waist value.
	2nd -X	Software function for caliper mid points.
	3rd -Z	Software function for caliper mid points.

4.13. INFRAMAMMARY FOLD

Landmark name:	Inframammary Fold	**LM body image:**
Pose:	Standing	
Typology:		
Description:	The circumlinear measurement of the inframammary crease was of the inferior 180° from the nipple [36]. "Located at the fifth–sixth rib. The lowest portion extends to the sixth intercostal space." [45]	
Landmark location:	Left and Right	
Measurements using landmark:	Apex spread apex depth, bust girth	
LM purpose:	Assign breast volume for size selection and locate apex for associated garment pattern fitting devices.	**LM pattern image:**
Features to narrow location:	The fold immediately below each the breast where the breast tissue meets the breast wall or rib cage.	
Discussion:	The inframammary fold may be somewhat manipulated by supporting breast garments and/or hidden by unsupported breast tissue (ptosis). The supine position increases the visibility of the inframammary fold [37]. "The natural boundaries of breast tissue are difficult to define with visual inspection only." [38]. "The inframammary crease is a known limitation for every major 3D surface imaging tool capturing the breast region in a standing posture." [39].	
Automated location:	Horizontal contour circumference taken below the bust. (Measurements 10, 75)	

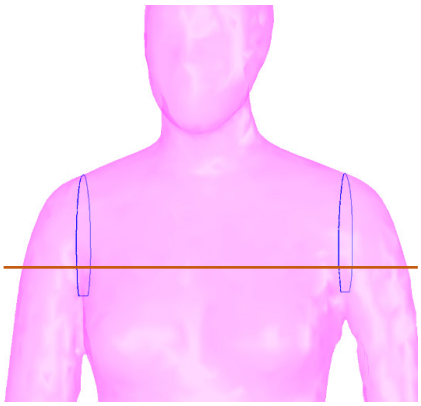
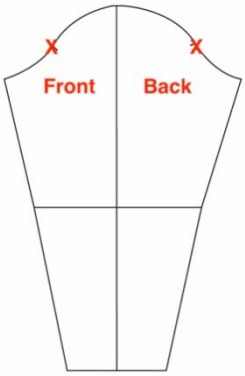
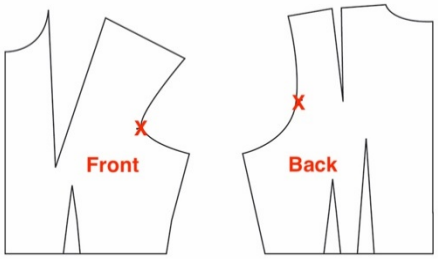
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 60% to 70% of total height. Using slicing curves at every 1 mm of height and using sagittal width curves at 40% and 60% of total width, determine the breast mound or transition to more vertical body curve or smaller soft tissue mound. If there is overhang, take height at intersection of body and overhang position. Software function for y height for intersection.
	2nd -X	Software function for caliper mid points.
	3rd -Z	Software function for caliper mid points.

4.14. BUST POINT

Landmark name:	Bust Point—Apex	**LM body image:**
Pose:	Standing	
Typology:	Left and Right	
Description:	The central point of the most anterior region of the breast mound. Defined by visual location of the central point of the most anterior region of the breast mound.	
Landmark location:	The point of the estimated thickest part of the left breast. When wearing a bra this can be considered an estimated location of the nipple.	
Measurements using landmark:	Under bust, bust circumference, side neck point to bust point.	
LM purpose:	Defines the key position from which to shape upper body garments to the female form.	**LM pattern image:**
Features to narrow location:	Breast shape in profile, anterior location of the breast mound.	
Discussion:	The nipple landmark is changeable depending on the breast support and therefore unstable [40]. Due to types of breast support creating a smoothed shaped, the most anterior point often refers to a 3 cm to 6 cm domed area. Here the bust point is the midpoint of the mound formed by the breasts support underwear.	
Automated location:	The most forward point of the left/right bust prominence measurement. (Landmark 105,106) When wearing a bra this can be considered an estimated location of the nipple. (Landmark 135, 136)	

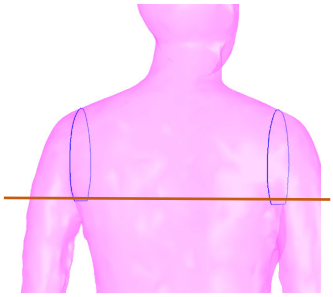
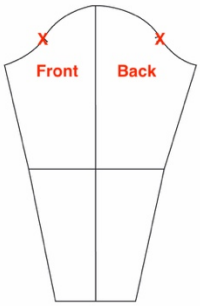
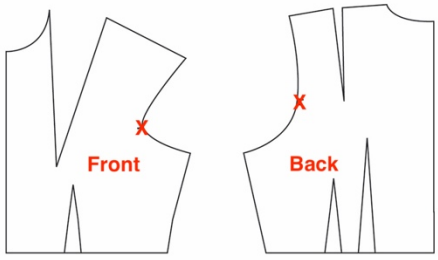
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 60% to 80% of total height. Using slicing curves at every 1 mm of height and using sagittal width curves at 40% and 60% of total width, determine the breast mound or transition to more vertical body curve or smaller soft tissue mound.
	2nd -X	Determine width location by intersection of front edge of bounding box for slicing curves at every 1 mm of height and breast mound curve for each breast at widths between 30% to 50% and between 50% to 70% of total width. Intersection point will determine x dimension for the curves with max absolute value of z. This may an average between points.
	3rd -Z	Front edge of bounding box with the max absolute value of z will determine max depth.

4.15. ARMSCYE FRONT

Landmark name:	Armscye Point front—Axilla left/right front	**LM body image:**
Pose:	Standing	
Typology:	Soft tissue (underlying muscle)	
Description:	Anthropometric apex of the upper arm and the lateral surface of the torso in the area of the front edge of the armpit fold. The point centered beneath the arm, where the arm intersects the chest. (Landmarks 15,16)	
Landmark location:	Left and Right	
Measurements using landmark:	Chest width Sleeve cap width Upper body depths	
LM purpose:	Allows segmentation of limbs from body to guide the width block between the armholes.	**LM pattern image:**
Features to narrow location:	A cross is marked first by a vertical line upward in the same plane as the knitting needle, then a perpendicular line at the top of the axilla folds Defines points on the back indicating minimum armhole depth, indicates torso width. Ensures the Axilla are determined by the width of the torso at its widest point before the branch of the arms. Pectoralis major is the muscle that sits at this point joining the arm to the body used in adduction.	
Discussion:	One side may be more prominent than another [30]; knitting needles placed horizontally high under a subject's armpit helps to identify location.	
Automated location:	Not defined, but chest measurement taken to front armpit points. (Measurements 87)	

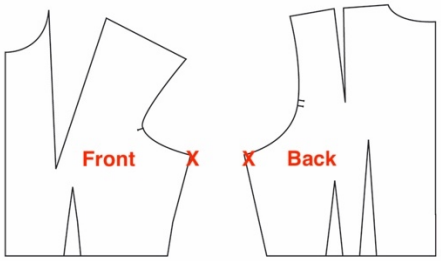
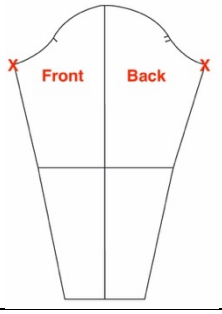
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 70% to 80% of total height, Repeat for both sides. Remove any independent arm curves from evaluation. Divide slicing curves at every 1 mm of height with x center slicing curve and repeat for both sides. For the front, use the height where the transition of the arc of the front curve and the arc of the arm transition intersect. Use x ranges to help with location.
	2nd -X	Use x ranges to help with location. Between 20% to 40% of total width and between 60% to 80% of width.
	3rd -Z	Software function for z value.

4.16. ARMSCYE BACK

Landmark name:	Armscye point back—Axilla back	**LM body image:**
Pose:		
Typology:	Soft Tissue (underlying muscle)	
Description:	Anthropometric apex of the upper arm and the lateral surface of the torso in the area of the back edge of the armpit fold.	
Landmark location:	A cross is marked first by a vertical line upward in the same plane as the knitting needle, then a perpendicular line at the top of the axilla folds.	
Measurements using landmark:	Across back width, scye width, upper arm diameter, across back width (armpit level)	
LM purpose:	Defines points on the back indicating minimum armhole depth, indicates torso width.	**LM pattern image:**
Features to narrow location:		
Discussion:	Often one side of folds is more prominent than another [30], posterior Axilla lower than anterior. Can be used to check scye level position Ensures the Axilla are determined by the width of the torso at its widest point before the branch of the arms.	
Automated location:	Tape measure measurement taken horizontally across the back of the chest between the back armpit points. (Measurements 88) The point centered beneath the arm, where the arm intersects the chest. (Landmarks 15,16)	

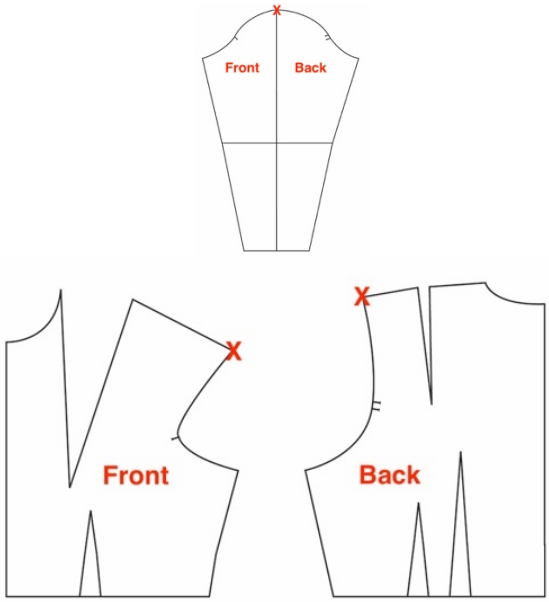
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 70% to 80% of total height, repeat for both sides. Remove any independent arm curves from evaluation. Divide slicing curves at every 1 mm of height with x center slicing curve and repeat for both sides. For the back, where the arc of back curve and arc of arm curve transition insect. Use x ranges to help with location.
	2nd -X	Use x ranges to help with location. Between 20% to 40% of total width and between 60% to 80% of width.
	3rd -Z	Software function for z value.

4.17. UNDERARM—ARMPIT MID

Landmark name:	Mid Underarm Armpit	**LM body image:**
Pose:	Standing	
Typology:	Soft Tissue (underlying muscle)	
Description:	The central point in the middle of the armhole position as determined by the front and back armhole points.	
Landmark location:	Left and Right	
Measurements using landmark:	Underarm length Side-seam length Divisional point for segmenting full circumference girths into front and back.	
LM purpose:		**LM pattern image:**
Features to narrow location:	Anterior and posterior armpit points.	 
Discussion:	Determines a midpoint in the armhole, support side seam division to create arcs from circumferences. If using this definition for arm circumference, the mid-point for the mid underarm point is an estimate. Contour circumference that passes under the armpit and vertically over the shoulder. If the arm is pressed against the side of the torso, the measurement uses an estimate of the underarm contour taken at armpit height.	
Automated location:	Not mentioned.	

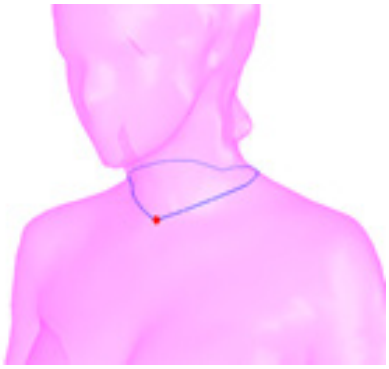
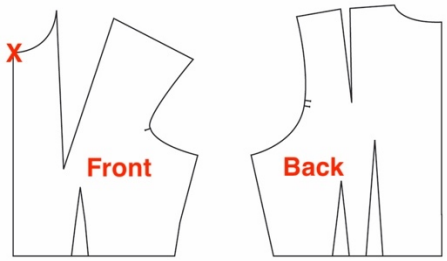
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 70% to 80% of height, repeat for both sides. After finding front and back points, set a slicing plane thru both points. Data evaluation will be required if results include blended data from arms and body. Determination if an arc or straight line to connect the front and back data points may be predetermined. The midpoint of arc or line will appropriate the y, x, and z values.
	2nd -X	Software function of intersection of slicing plane, mesh, and arc or line.
	3rd -Z	Software function of intersection of slicing plane, mesh, and arc or line.

4.18. SHOULDER POINT

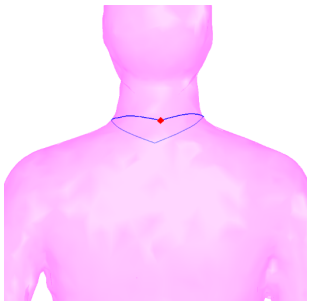
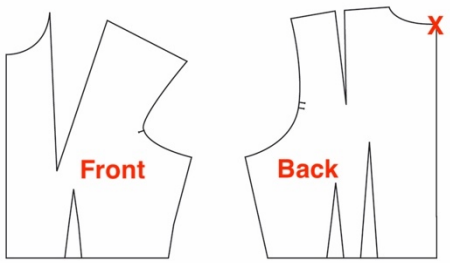
Landmark name:	Shoulder (Acromial)—left/ right	**LM body image:**
Pose:	Standing pose	
Typology:	Skeletal	
Description:	Intersection of the upper outer edge of the acromion growth and the vertical plane of the shoulder joint on the skin. The point on the superior aspect of the most lateral part of the acromion border [31] p. 53.	
Landmark location:	Left and Right	
Measurements using landmark:	Arm length, armscye curve length, shoulder length, defined from the acromion angle to the most anterior aspect.	
LM purpose:	Identifies a joint point for movement concerns. Creates a shoulder length when combined with side neck point to distinguish front from back body.	**LM pattern image:**
Features to narrow location:	Shoulder area, arm position, armhole, acromion as a projection of the scapula. Defined as the angular change between the plane of the shoulder and plane of the arm and in relation to the underarm point.	
Discussion:	Subject to variation due to posture, musculature, skeletal features, and position of arm. The end point for shoulder defines a break point between the body of the garment and the sleeve. The garment may be made symmetrical even if left/right shoulders vary, so how to reconcile discrepancies is of concern.	
Automated location:	Method 1—The point of greatest curvature along the front silhouette of the shoulder. Method 2—Shoulder Angle double 10.0. Furthest point on the body from the armpit, measured at the given shoulder angle. (Landmarks 13, 14)	

Sequence for semi-automated virtual landmarking:	**1st -Y**	Narrow the y position to a range of 80% to 90% of height using slicing curves at every 1 mm of height. Define a maximum height within a region less than 40% and greater than 60% of total body width. Locate the shoulder point on the perimeter of the body where the height transitions to arm. Both left/right sides must be identified. Curvature of the shoulders will impact the final location. Discrepancies may be reconciled (average or maximum) or output with possible asymmetry. The x, z coordinates are identified with reference to the assigned ground zero.
	2nd -X	Software function for x values.
	3rd -Z	Software function for z values.

4.19. FRONT NECK POINT

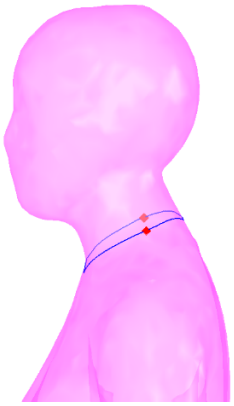
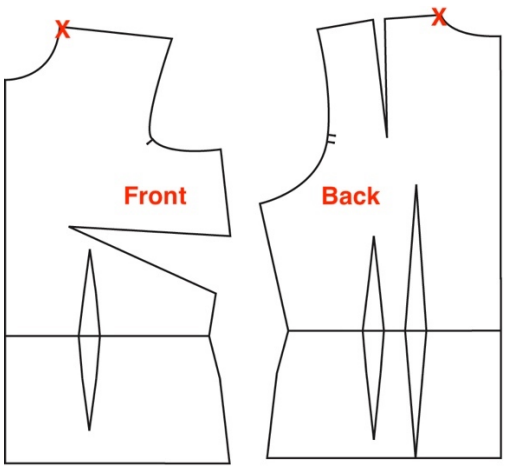
Landmark name:	Front Neck Point		**LM body image:**
Pose:	Standing		
Typology:	Skeletal		
Description:	The anthropometric point above the yoke (suprasternal notch) at the base of the neck. The anthropometric point above the yoke (suprasternal notch) at the base of the neck.		
Landmark location:	Midline		
Measurements using landmark:	CF Length		
LM purpose:	Defines the front edge of the neck to shape a collar.		**LM pattern image:**
Features to narrow location:	Suprasternal notch (incisura jugularis sternalis).		
Discussion:			
Automated location:	The point where the front of the neck column intersects the shoulders. (Landmarks 1)		
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 70% to 90% of total height. Starting at 90% of total height and within 40% to 60% of total width range, slicing curves at every 1 mm of height, find the lowest height that the slicing curve has an arc away from front edge bounding box edge.	
	2nd -X	Project line from front edge to the arc in the curve, end point will have x value. Software function of point.	
	3rd -Z	The same projection line from front edge to the arc in the curve, end point will have z value. Software function for z value.	

4.20. BACK POINT NECK

Landmark name:	Back Neck Point	**LM body image:**
Pose:		 
Typology:	Skeletal	
Description:	The superior palpable point of the spine of the 7th cervical vertebra at the posterior base of the neck The point where the back of the neck column intersects the shoulders. (Landmarks 2)	
Landmark location:	Midline	
Measurements using landmark:	Upper back length (neck to across back width (armpit level). Neck to center waist back.	
LM purpose:	Segmentation of head from torso. Defines a central point at the posterior neck critical for mapping to garment patterns.	**LM pattern image:**
Features to narrow location:	Palpate downward from the back hairline to locate the protrusion of the 7th cervical vertebra at the base of the posterior neck.	
Discussion:	Considerable variability in prominence of C7 bone at base of back neck (spinous process of the seventh cervical vertebra). Neck extension causes C6 to sink making C7 easier to palpate but Cervicale height measurements only made from non-distorted position ISO 7250-1: 2017 [43] with erect head ASTM D5219-15 [35]. If the C7 is not palpable, it can be estimated with regard to a tape measure across shoulders [17].	
Automated location:	The point where the front of the neck column intersects the shoulders. (Landmarks 2)	

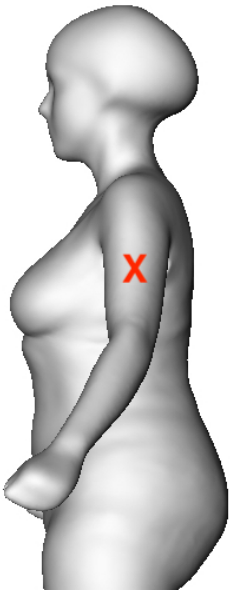
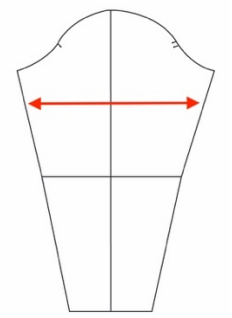
Sequence for semi-automated virtual landmarking:	**1st -Y**	Starting at 90% of total height and within 40% to 60% of total width range, using slicing curves at every 1 mm of height, find the closest point of the curve to the back edge of bounding box of each curve, create a ridge curve, find the highest height of transition from the neck to shoulders by slope of curve.
	2nd -X	Software function of point. The x value of the back point may not be the same as the front neck point.
	3rd -Z	Software function for z value.

4.21. SIDE POINT NECK

Landmark name:	Side neck point	**LM body image:**
Pose:	Any	
Typology:	Soft Tissue	
Description:	A point in the mid shoulder plane where the shoulder and neck meet at the intersection created by the trapezius, scalenes, and sterno-cleido-mastoid muscles. The side neck point marks a change in angle from the shoulder to the neck.	
Landmark location:	Left and Right	
Measurements using landmark:	Starting point for length measures. Shoulder length.	
LM purpose:	Segmentation of head from torso. Denotes the division between the front and back neck arcs.	**LM pattern image:**
Features to narrow location:	The intersection of a neck chain (passing posteriorly over the C7 and anteriorly over the clavicles) and the trapezius muscle, where it moves between the shoulder and neck column, denotes the side neck point.	
Discussion:	Body division point critical for pattern mapping, influenced by anatomy, and key for posture and shape analysis [41]. Robust landmark definitions in virtual environments requires a coupling of anatomical knowledge with an appreciation of surface geometry captured through body scanning and recognition of the application of the LM [42].	
Automated location:	The point where the left (right) side of the neck intersects the chest, on the peak of the shoulder ridge or in front of just the shoulder ridge. (Landmarks 3,4)	

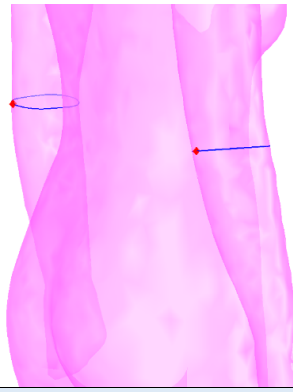
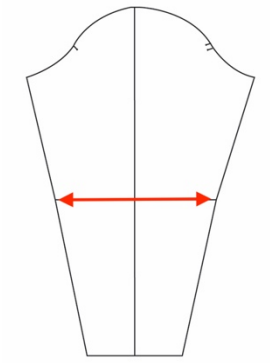
Sequence for semi-automated virtual landmarking:	**1st -Y**	Starting at 90% of total height and within 20% to 80% of total width range, using slicing curves at every 1 mm of height, using the right and left edges of bounding boxes of each curve, create right and left ridge curves, find the highest height of transition from the neck to shoulders by slope of ridge curve. The heights may be different for each side.
	2nd -X	Software function for x values.
	3rd -Z	Software function for z values. These may be different for each side.

4.22. BICEPS—UPPER ARM GIRTH

Landmark name:	Biceps/ Upper Arm Girth/ Upper Arm Circumference	**LM body image:**
Pose:	A-pose	
Typology:	Soft Tissue	
Description:	Relaxed arm girth at the level of the mid-acromiale-radiale site (the mid-point of the straight line joining the acromiale and the radiale), perpendicular to its long axis of the arm and using a metal tape [31] p. 105. Tensed arm girth perpendicular to the long axis of the arm at the level of the peak of the contracted biceps brachii, using a metal tape measure [31] p. 106. BS EN ISO 7250-1 flexed upper arm circumference with the arm extended horizontally forward, the elbow flexed about 90° and the fist is clenched [43]. ISO 20689 refers to BS EN ISO 7250-1 as above and held facing the head [15]. ISO 8559-1: maximum girth of upper arm at lowest scye level and measured with arms hanging naturally [26].	
Landmark location:	Left and Right	
Measurements using landmark:		
LM purpose:	Sleeve girth	**LM pattern image:**
Features to narrow location:	Below the armpits and above the elbow, maximum circumference.	
Discussion:		
Automated location:	Largest circumference of the upper right (left) arm taken along the axial cross section of the arm. (Measurements 89,90) Tape circumference of the right (left) arm taken at armpit height along the upper arm axis. (Measurements 234, 235)	

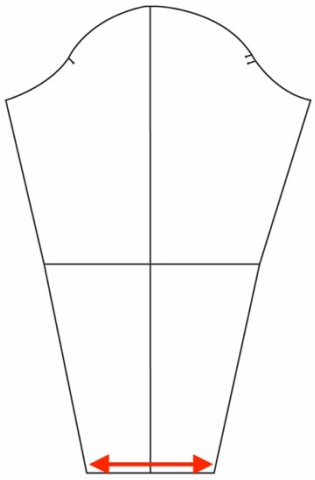
Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 70% to 80% of height. Repeat for each arm. From the armpit midpoint through to the elbow, determine the angle of arm in the x dimension. Create axial cross section slicing planes for both regions at every 1 mm of height. If the curves for the arms and body are bridged together, trim curve at bridging and create a connecting line or arc between ends of curve. The connecting line or arc may be up to 35% of total circumference.
	2nd -X	Software function for caliper mid points.
	3rd -Z	Software function for caliper mid points.

4.23. ELBOW

Landmark name:	Olecranon—Elbow	**LM body image:**
Pose:	A-pose	 
Typology:	Skeletal and or soft tissue	
Description:	The most superior point on the posterior elbow defined by a bony protrusion of the olecranon at the proximal end of the ulna. Radiale: The point at the proximal and lateral border of the head of the radius (ISAK, 2019, p. 55). Humeral Epicondyles, skeletal landmarks on the lateral and medial aspects of the humerus. Ante cubital fossa, indent formed on the anterior aspect of the arm, due to the insertion points of the bicep and forearm muscles.	
Landmark location:	Left and right mid arm.	
Measurements using landmark:	Elbow depth. Sometimes used to narrow location of bottom of ribcage and waist.	
LM purpose:	Determines the elbow level on a sleeve and can guide decisions on sleeves. Helps with determination of placement of shaping for the valgus angle in two-piece sleeves.	**LM pattern image:**
Features to narrow location:	Use the index finger to palpate a point at the centre of angular change between the rear and bottom of the olecranon. Flexion of the elbow can help ensure this point remains most superior.	
Discussion:	Defines the position of the elbow on the back-arm line, indicates shaping point for the sleeve. Non-prominent Olecranon makes it harder to determine from the scan surface.	
Automated location:	The centered back point of the left (right) elbow circumference. (Measurements 122, 123) (Landmarks 123, 127)	

Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 60% to 70% of total height. Repeat for each arm. Since this is an A pose, determine the angle of each arm. Using that angle, create axial slicing planes at every 1 mm of height. Find either the transition from upper to lower arm or back elbow max point. If the curves for the arms and body are bridged together, then find the arm curve that portion, trim curve at bridging and create a connecting line or arc between ends of curve.
	2nd -X	Software function for x values.
	3rd -Z	Software function for z values.

4.24. WRIST

Landmark name:	Wrist	**LM body image:**
Pose:	Any	
Typology:	Skeletal	
Landmark location:	Left and right between arm and hand	
Measurements using landmark:	Sleeve length Wrist girth	
LM purpose:	Used when shaping a sleeve. Segmentation to indicate division of hand from arm.	**LM pattern image:**
Features to narrow location:	Ulna Styloid Forearm Muscle Hand shape Wrist crease	
Description:	Measurement of the perimeter of the wrist base, covering this joint with a measure tape in a plane perpendicular to the forearm. The minimal girth of the wrist perpendicular to the long axis of the forearm, distal to the styloid processes [31] p. 108.	
Discussion:		
Automated location:	Circumference at the left/right wrist joint below the bone. This measurement is dependent on the subject gripping the handholds during scanning. (Measurements 93, 94) (Landmarks 103,104)	

Sequence for semi-automated virtual landmarking:	**1st -Y**	Range: 50% to 60% of total height for arms only. Repeat for each arm. Determine the angle of each arm from below elbow height. Using that angle, create axial arm slicing at every 1 mm of height. Starting just above the fist or hand for a specified number of slices, find max circumference.
	2nd -X	Software function for x values.
	3rd -Z	Software function for z values.

5. CONCLUSION

The inaccuracies of current body-to-pattern mapping processes make critical assessment of measuring the body very difficult. Just as virtual fitting has evolved with better linking to the body pattern, so too must landmarks be better defined. Technology provides a means to consider new landmarks specific to creating data to drive clothing. This also drives a need to understand how decisions made based on proportional expectations in pattern drafting directly relate to the specific individual body.

Understanding the relationship between body and product relies on precision of landmarking. For example, the degree to which a shirt rises when arms are raised is measurable. How much of this measurement is related to shoulder restrictions and how much is related to movement of the underarm can only be isolated with precise location of the underarm, shoulder, and hip landmarks. With body measurements being dynamic, changing even with breath, certainty of landmarking precision would go far toward understanding how such variability affects product design (e.g., apparel fit). 4D body scanning to assess dynamic body measurements [44] stands to further our understanding of dynamic measurements but reliability is paramount. Standards definitions that encourage practice suitable for both physical and digital practice have become urgent. Improved landmarking suitable for wildly varying human morphology may well be a segue for improved adoption of 3D technologies. Future study should focus on methods for repeatable landmarking toward this goal. This will allow better correlation of body-to-pattern landmarks and the true benefits of 3D technologies to drive virtual fitting applications (improved garment fit and mass customization) can be realized.

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