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Proposed landmarking for improved digital product creation

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ABSTRACT

Sampling is a critical step in the concept-to-style workflow for digitally created products. Virtual environments allow sampling without the costs associated with physical prototyping However, current practice often still requires physical prototyping. Here we consider how flaws in landmarking practice contribute to the need for iterative sampling, thereby inhibiting a fully digital product creation DPC process. The opportunity for error within traditional anthropometric study is highlighted and a path toward global standardized landmarking and measuring (L&M) is presented. Landmarks denote anatomical reference points common to all humans. They are critical to every stage of DPC: measuring, product development, virtual sampling, rigging, size selection, and try-on. Cross-platform use of humanoids (models of humans) and body-worn products will introduce error if landmarking protocols do not align across three-dimensional body processing (3DBP) technologies. Here we discuss how to avoid these discrepancies by combining Clone Block™ theory with current ISO standards. Further study to enable effective 3D technology interoperability, full DPC, and greater adoption of 3D technologies with improved fit of body-worn products is proposed to validate the method described herein for more effective L&M driving fully digital product creation.

Keywords
Clone Block™,
global standardized landmarking and measurement,
feature points,
apparel fit,
rigging,
rig,
virtual fittings,
3D sampling

1 Introduction

In 2004, researchers from Cornell University confirmed that 3D virtual environments permitted the visualization of the commonly held principles of fit (set, line, balance, ease, and grain) and had the potential to replace live fit sessions (4D study). They concluded that virtual fit testing would lead to the "development of better fitting apparel" [1], but this has yet to come to fruition. Virtual environments have minimized sampling and reduced some of the costs associated with prototyping, but fit validation continues to be a heuristic endeavor that frequently requires physical prototyping. Here we cite studies of disparities in global measuring practice at different stages of digital product creation [2-4] as the root cause inhibiting fully digital product creation. Studies of variation in hip and waist landmarking [5,6] and studies proposing various methods of locating common landmarks [7-9] demonstrate continued efforts to define and address this issue. The following comment sums up the net negative impact of landmarking and measuring (L&M) practice on digital product creation:

"A lack of standard L&M protocols is inhibiting supply chain interoperability. Three service providers along the development chain may define the waist of a given fit model at a different location. As a result, product development files are not transferable between apparel pattern and animation software. Ideation requires universal standards. We should have a method of body measurement that sticks with the humanoid through all programs." (personal video call with Katherine Schildmeyer, 3D animation & fit specialist, November 2022)

This lack of standardized global L&M practice has proven to be a significant hurdle for selling apparel products [10,11] with the following compounding effects on digital practice:

- A defined waist and hip in one size chart may reference a completely different body cross-section in another size chart.
- Size selection has a built-in flaw in comparing cross-sectional planes from different proportional heights within body regions.
- Coveroid engineers and humanoid animators continuously modify landmarks on coveroids and humanoids between software applications, or worse, they do not make this adjustment, and an error is introduced.
- Parameterization of humanoids may be generated from mismatched cross-sections resulting in body-shapes not fully representative of the desired form.
- Virtual fittings are transpiring from a place of error since the humanoid and coveroid are oriented with few common alignment points.

Landmarks are critical to every stage of digital product creation (DPC): measuring, product development, virtual sampling, rigging, size selection, try-on, and reselling [12]. They denote morphological points of reference common (barring dismemberment) to all humans. For apparel fit validation, landmarks serve as the base points of reference for gauging fit errors. For apparel product development, landmarks on the humanoid mesh drive coveroid geometry. For human animation, landmarks connect weights to positions (joints and sites) on the virtual skeleton (rig) to drive humanoid movement. For parametric resizing of humanoids, landmarks denote areas of morphological variability scaled to twin human morphology. As detailed in Appendix 1, landmarking and measuring (L&M) protocols have long been a global point of contention within the apparel industry.

Cross-platform use of humanoids (models of humans) and coveroids (models of covers understood to be any body-worn products) is sure to be fraught with error if landmarking protocols do not align across three-dimensional body processing (3DBP) technologies. Table 1 details just one case where a lack of standardized L&M practice can have profound implications on product development. In this table, methods 2 and 3 position the front and back neck points a set distance from the side neck. Consequently, if the custom dimensions received from extraction software are not adjusted to compensate for this prescribed (rather than custom) pattern dimension, both the neck shape and torso length dimensions will be in error. Pattern-making method 1 avoids this problem by mapping the front and back neck relative to the side neck yet faces other potential errors. The front neck depth for mapping practice 1 may be incorrect if the center front length in method 1 is not acquired as a dimension bridging the breast mounds (as discussed by Ahmed et al.) [8]. As the apparel industry continues to adapt traditional practices suitable for 3D technologies, such disparity is often overlooked (personal e-mail communication with Susan Ashdown October 2022).

Table 1. Side neck discrepancy requiring varied landmarking practice.

	Textbook	Front neck depth	Back neck depth	Front neck width	Back neck width	Front axilla depth	Back axilla depth
1	Pattern-making for Fashion Design [13]	It is inferred as the difference between the princess and center lengths.				As measured	
2	Metric Pattern Cutting [14]	20% of neck girth less 2mm	15 mm	20% of neck girth less 2 mm	20% of neck girth less 7 mm	Measured depth from side neck but an estimated back neck depth/rise may cause a length conflict.	
3	Computer-Aided Pattern Design & Product Development [15]	20% of neck girth	Assigned as a 20 mm rise, not a depth	20% of neck girth less 15 mm	20% of neck girth less 5 mm		

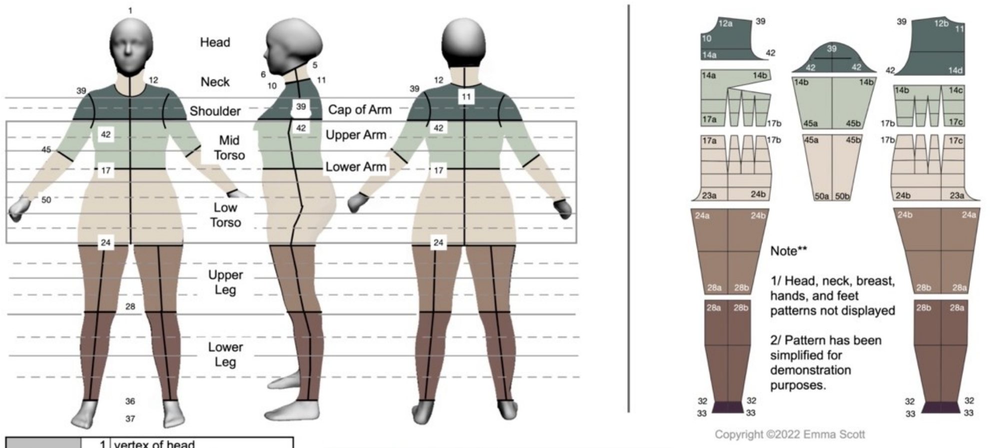
This paper will discuss where landmarking discrepancies inhibit efforts toward a fully digital product creation (DPC) workflow, offer theory toward global standardized landmarking and measuring (L&M) practice for further confidence studies, demonstrate how such a theory can work within established practice without disruption, and establish the possibility for the theory to solve urgent challenges for the widespread adoption of 3DBP technologies. Standardized L&M of humanoids and coveroids would offer a significant step forward for DPC, solving long standing known challenges [10] (see Appendix 1).

Discussion here is the culmination of an extended conversation with the Institute of Electrical and Electronics Engineers 3DBP Industry Connections Working Group (IEEE 3DBP IC WG) over five years (2017-2022). The group comprises a unique group of industry experts representing the disciplines involved in 3DBP activities: engineering, business, management, consulting, computer architecture, machine learning, animation, AR/VR/XR, fashion design, academic apparel design, anthropometry, and pattern engineering. All discussion has been concerned with interoperability. IEEE 3DBP IC WG participants from Apparel, Footwear, and Wearables supply chains exchange challenges to interoperate global 3DBP technology. Adoption is the vision, but non-technical problems continue to inhibit technology diffusion. A pivotal model from the group is the "assets and transformations model" concerning the activities of modeling, donning, and doffing apparel. The discussion here utilizes this model where the activities of modeling and donning garments are summarized as the transformations between four assets: human, cover, humanoid, and coveroid. Within this model, a cover is understood to be any body-worn product on a human, while coveroids and humanoids are understood to be models of physical objects [16].

2 Global standardized landmarking and measuring for cross-platform compatibility

2.1 Defining body regions as the common ground

The first step toward standardized measuring practice was careful examination of the primary standards governing the modelling, donning, and doffing of apparel to determine the common ground between the activities of humanoids and coveroids. A review of ISO 8559-1:2017 [17], ISO 18825-1-2016 [18], ISO 18825-2-2016 [19], and ISO / IEC 19774-1: 2019 [20] highlighted the importance of segmenting the body into regions for honed analysis. Humanoid segmentation is a required step for the automated extraction of landmarks, highly correlated with the rigging of virtual skeletons, and a driver for the parameterization of humanoid body-shape. This sub-division of the body into regions is also prevalent with anthropometric study, data analysis, size chart development, and apparel pattern blocks (coveroids). Therefore, body regions were defined as the common ground between disciplines related to the study of humanoid and coveroid interaction. Figure 1 illustrates the direct humanoid-to-coveroid relationship established with perimeter landmarks denoting body regions.



Head	1	vertex of head
	5	back high-neck (C1)
	6	front high-neck (C3)
Neck	5	back high-neck (C1)
	6	front high-neck (C3)
	10	front low-neck (T2 - derived)
	11	back low-neck (C7)
	12	side neck (half calliper)
Shoulder	10	front low-neck (T2 - derived)
	11	back low-neck (C7)
	12	side neck (half calliper)
	39	shoulder - acromion (T3)
	14	chest (T6-T7)

Mid-Torso	14	chest (T6-T7)
	42	underarm (T8 1/2 caliper)
	17	high-waist (L1-L3 - 37.5% chest-gluteal)
Low-Torso	17	high-waist (L1-L3 - 37.5% chest-gluteal)
	24	high-thigh (average of gluteal points)
Upper Leg	24	high-thigh (average of gluteal points)
	23	crotch (perineum 1/2 caliper highthigh)
	28	knee (patella)
Lower Leg	28	knee (patella)
	32	ankle (lateral malleolus)
	33	floor / heel landing point

Cap of Arm	39	shoulder - acromion (T3)
	14	chest (T6-T7)
	42	underarm (T8 1/2 caliper)
Upper Arm	42	underarm (T8 1/2 caliper)
	45	elbow
Lower Arm	45	elbow
	48	wrist (ulna stylion)
	51	overhand - pinky root

Fig. 1 Body regions defined by stable landmarks.

2.2 Defining the activity of 4D study

The next step was to consider how body regions are observed during movement and 4D study. Dimensional change to either the humanoid or coveroid is observed as the expanding or contracting of measurements between base points of reference within, and between body regions. Landmarks were therefore sub-classified as stable or non-stable. Stable landmarks define the perimeter boundaries of body regions. Barring human dismemberment, stable landmarks, connect all humans regardless of age, height, or gender. The common nature of these points (e.g., bust, waist, hip girths) explains their widespread use in sizing practice. Non-stable landmarks define morphology within body regions. Non-stable landmarks denote morphological areas of interest within a designated body region and those points expected to demonstrate a dimensional change in morphology through movement. The uncommon nature of these points explains why brands will offer products in shape categories. For example, brands may offer slim and relaxed fit jeans not only for styling but also to accommodate extremes in thigh girth within the upper leg region.

Figure 1 details the stable landmarks identifying the body regions and establishing a direct humanoid-to-coveroid relationship. Within each of these regions any number of morphological landmarks may also be identified. From this base A-pose relationship, we can define 4D study as the observation of changes between and within body regions. Between body regions we would observe changes between the common stable perimeter landmarks. For example, a figure bending forward would create length discrepancies between the mid and low torso body regions at the common stable high-waist landmark. On the front of the body an excess of length would be noted while the back body would experience a lack. Within the body regions, a misalignment of humanoid and coveroid non-stable landmarks would be noted.

The pattern pieces in Fig. 1 relate to the left half of the body and hint at an equally important discussion regarding body weight distribution; the variation in body volume from left-to-right, and front-to-back.

Traditional discussions regarding placement of quarter body divisional lines often confuse aesthetic choice for placement of design style lines with body dimension fact. This is because traditional methods encourage practitioners to take measurements from the location of the 'desired' seamline on the body. Since the art of design relies on unique choice, consensus on divisional body lines is impossible. Here, we suggest preference for left-to-right, and front-to-back divisional style lines [21] should remain opinion based while caliper widths and depths on cross-sectional planes be used for factual body data. This provides agnostic globally understandable data regarding girth distribution without imposing restrictions on pattern-engineers and their proprietary practice. Indeed, the use of caliper widths and depths stands to improve our understanding of the humanoid-to-coveroid relationship by encouraging coveroid engineers to ask, “what decisions am I making to achieve this seamline from this factual body data”.

2.3 Identifying the challenge for global standardized L&M

Understanding the significance of body regions and stable landmarks underscores a potential flaw within traditional size chart practice. Note how the traditional assignment of waist and hip (letters in Fig. 2) places the key size chart girths [22] at varying, and somewhat random, heights within the torso region. The traditional understanding of the waist is that it may move vertically up or down with weight change. This assumption, however, can conflict with traditionally sized production patterns which are made for static height cross-sectional girths. Furthermore, a cross-sectional plane understood to move up or down with weight change does not provide a base point of reference with which to understand changes in body-shape. For example, a traditional understanding of a pregnancy waistline suggests the aesthetic position of a waist style line should rise or lower to accentuate the smallest torso girth. From this understanding it can be observed that waistlines move up or down depending on other body-shape characteristics. Such observation, however, offers style but not body-shape data. A more accurate understanding of the effects of weight change is achieved by monitoring a static cross-sectional girth referenced to skeletal points throughout the pregnancy. Referencing girth planes to skeletal structure offers stable base points of reference. Assignment of girths at random heights inhibits a one-to-one comparison of humanoid and coveroid cross-sectional planes.

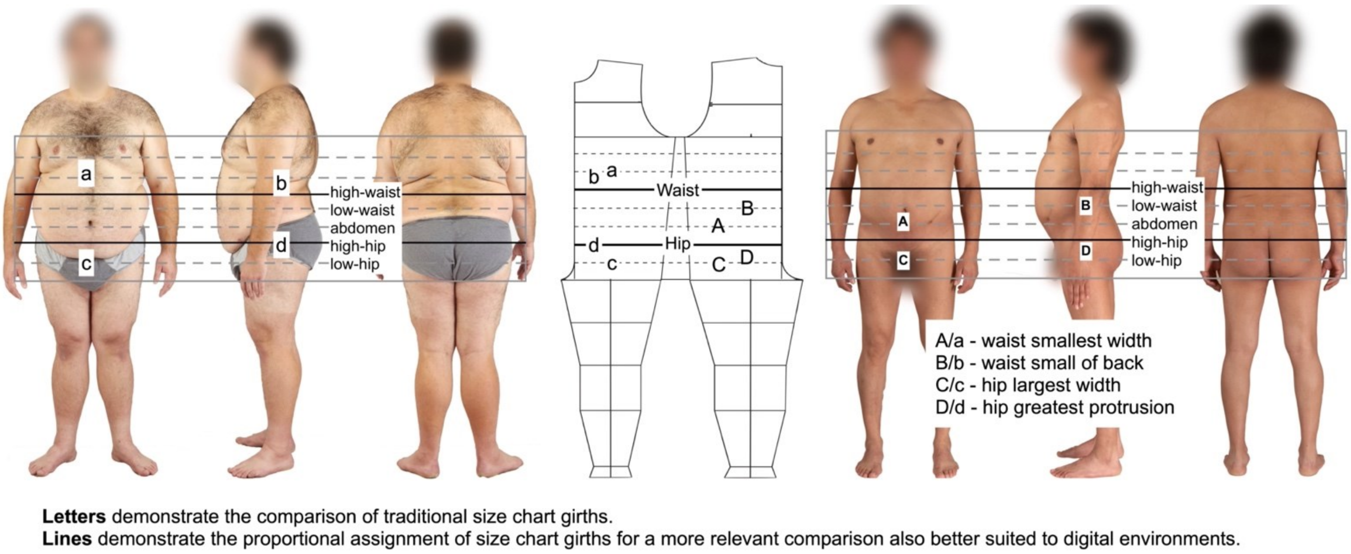


Fig. 2 Proportional assignment of girth landmarks improves size selection reducing garment returns.

Research here suggests the usefulness of morphologically assigned landmarks (such as the waist and hip) for size chart practice should be reassessed. As illustrated by the letters in Fig. 2, such practice can lead to a comparison of random cross-sectional planes without cross-population relevance. To circumvent this challenge, the lines in Fig. 2 illustrate a different approach; size chart dimensions assigned as proportional divisions of body regions. Note how the derived girth lines present cross-sectional planes with a skeletal relationship common to the torso body region across subjects. The subject of common points of cross-populational reference, while not inherent in traditional apparel practice, is well established in the field of biomechanics [53,54].

2.4 Working within established practice without disruption

The use of girths derived relative to skeletal structure in no way negates the importance of landmarks assigned as per traditional practice. Morphological landmarks provide necessary data about body-shape, but, as with all choices concerning opinion, decisions will not be unanimous. Consequently, thirty years of concerted effort toward apparel digitization has yet to resolve controversy on the 'best' location for the waist or sideseam landmarks [3,21,23]. Here we propose the use of proportional division of body regions as a standardized method for assigning cross-sectional planes with universal relevance. The use of caliper widths and depths on these planes presents an agnostic method for assigning split lines to create side and center body lines to achieve detailed size chart dimensions. This permits ground truth body dimensions to be separated from style line discussions. From these base points of reference, practitioners may continue to utilize morphological landmarks referenced as a measured distance above or below a proportional girth. For example, in Fig. 2, the first subject's narrowest waist width would be 5.5 cm above the designated high-waist cross-section while the second subject's narrowest waist width would be 10 cm below. The assignment of a morphological waist(s) relative to proportionally assigned cross-sectional girths permits a universally common, and repeatable method for assigning size chart girths while avoiding controversy surrounding the most aesthetically pleasing location for design lines. The placement of style lines may continue as suited to the practitioner, while measuring practice is provided universally agnostic methods.

3 Results

The following section offers a summary for the proposed practice; to evolve traditional L&M practice to be better suited for digital workflows while working within highly established apparel practices. The suggested practice combines Clone Block™ landmarking and measuring [24-26] with ISO standards [17-20]. Discussion here focusses on the regions significant to general apparel practice: shoulder, torso, arm, and leg body. The head, neck, hands, and feet body regions require a depth of discussion outside the scope of content possible here, so only landmarks relevant to apparel openings (overhead, over-hand, and over-foot) are discussed. Appendix 2 details the landmarks required for the suggested global standardized practice.

3.1 Assign stable morphological landmarks

Extraction of measurements from body scan data has been the subject of concerted effort resulting in techniques suited to various data formats and an even wider variety of unique morphologies [27-33]. Challenges with acquiring 'accurate' body data continue to plague efforts toward automation. Appendix 3 identifies the stable landmarks for which automated measurement extraction algorithms are required. Figure 1 and Appendix 2 indicate landmarks derived from the stable landmarks. For fully digital product creation the stable landmarks denoting body region boundaries (from surface feature points) must be defined such that automated extraction algorithms can produce reliably repeatable results. Following are the challenges with stable landmarks noted during this study and for which further standard direction (for repeatable methods for locating these critical landmarks) will be required to facilitate forward apparel digitization efforts.

1. Low-Neck – Current automated landmarking methods have difficulty accurately assigning the front, back and side neck positions on forward thrust necks and on necks with substantial adipose tissue. Further, the positioning of the front neck is often accomplished as the inflection point of curves (coming off the body and neck) rather than at a point relative to the clavicles. The location of the low-neck points is essential for accurate fitting of the neck region. Automated landmarking of this area must improve.
2. High-Waist – processing of a larger data set (e.g., Civilian American and European Surface Anthropometry Resource) should validate the current allocation of high-waist at 37.5% of chest to gluteal or suggest an adaptation for locating this critical stable body region landmark.
3. Upper and lower scapula – modeling of unique and complex shoulder variation requires the addition of scapula points which require further study and direction for landmarking. Figure 4 illustrates these points aligned in 'x' with the side neck and with 'y & z' derived relative to other cross-sectional girth planes. Further testing will establish this positioning.

3.2 Derived global standard size chart girths

Figure 3 illustrates how percentage division of body regions permits size chart girths (lines) to be normalized for a common skeletal relationship relative across gender and height categories. Without this it is possible that cross-sectional girths from different body regions are being compared (letters). The lines in Figure 3 illustrate the relative comparison of skeletally assigned girths. The letters in Figure 3 illustrate how morphologically assigned girths will not always result in a one-to-one comparison. This figure therefore illustrates a potential flaw with current size selection processes which could increase the risk of inaccurate size selection and product returns.

Fig. 3 Age and gender-neutral assignment of size chart girths for standardized L&M.

Varied vertebrae spacing and spinal deformity [34] result in drastic length and height variability across a global population. Morphological assignment of girths within such height variability can result in a comparison of cross-sectional planes at different skeletal locations. To reduce this risk, Clone Block™ theory derives key size chart girths as a percentage division of body regions. Other research concurs with the possible use of proportional division for locating key girths [5,6]. One study suggests locating the sacroiliac joint as a percentage of the distance between the gluteal and the back neck vertebra (C7-T1) [31]. However, this would not be effective for apparel design as it distributes possible upper spinal deformity throughout the entire torso region. As discussed in the book "Draping for Apparel Design" [35], body region boundaries are significant to apparel design as points where fabric grain is corrected to align with horizontal and vertical humanoid cross-sectional planes. Figure 4 illustrates the horizontal and vertical body region boundaries of theoretical importance to fabric grain. Spinal asymmetry [34] and vertebrae variation [24] can result in a skewing of grain away from the desired alignment. The left side of the diagram in Figure 5 illustrates locations where such skeletal variation may be accommodated. This is possible because the perimeter boundaries of the body regions relate to balance areas where theoretical adjustment to fabric grain is accommodated. The following are possible skeletal variations which would require adjustments to fabric grain to reduce buckling:

- The neck region is affected by cervical lordosis (e.g., forward thrust neck), indicating a change in vertebrae concentrated in the C6-T3 area and resulting in a more pronounced concave shape between high-neck and low-neck.
- The shoulder region is affected by thoracic kyphosis (e.g., rounded shoulders), indicating a change in vertebrae concentrated in the T5-T8 area and resulting in a more pronounced convex shape of this region between the chest and ribcage.
- The lower torso region is affected by lumbar lordosis (e.g., foreword tilted pelvis), indicating a change in vertebrae spacing concentrated in the L1-L5 area and resulting in a more pronounced concave shape between the high-waist and abdomen. Further, the effects of both thoracic kyphosis and lumbar lordosis can extend into the neighboring region, causing length changes concentrated around the waist area at T12-L2 [36,37].
- The legs due to positional variation of the knee under the pelvis (knock-knees or bowlegs) may require length adjustment between the upper and lower leg regions.

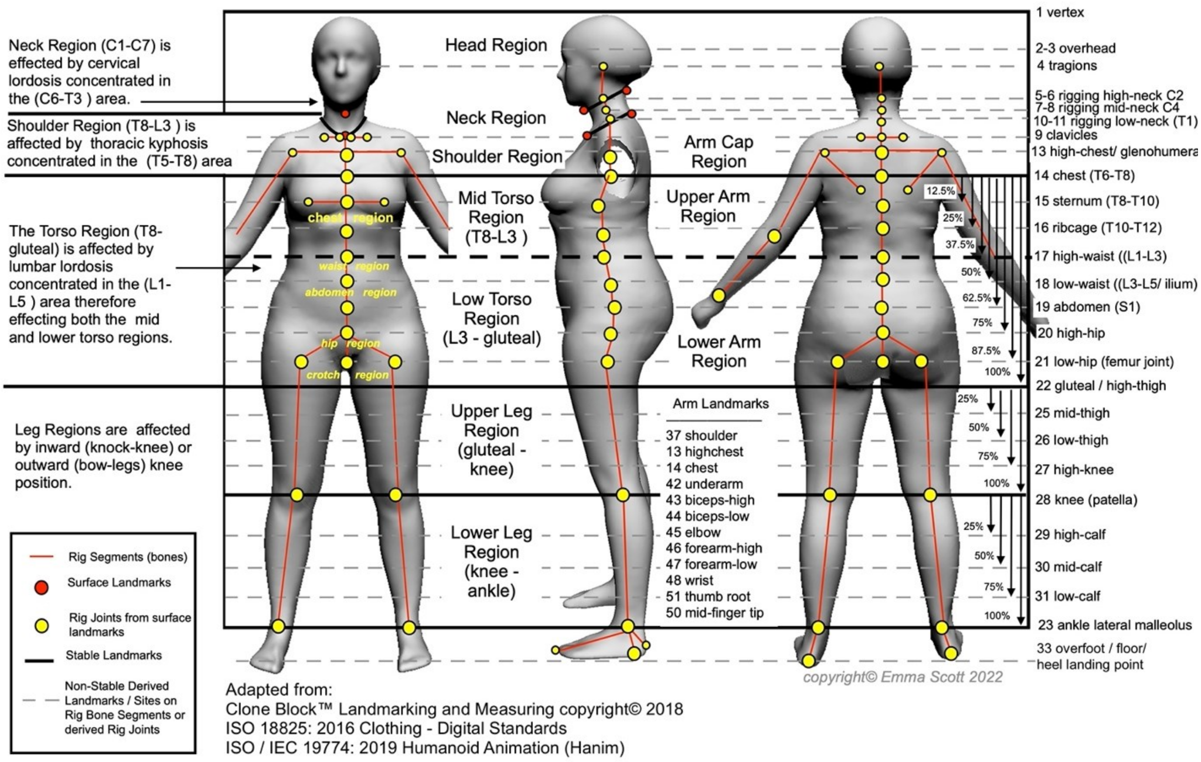


Fig. 4 Standardized L&M for fully digital product creation.

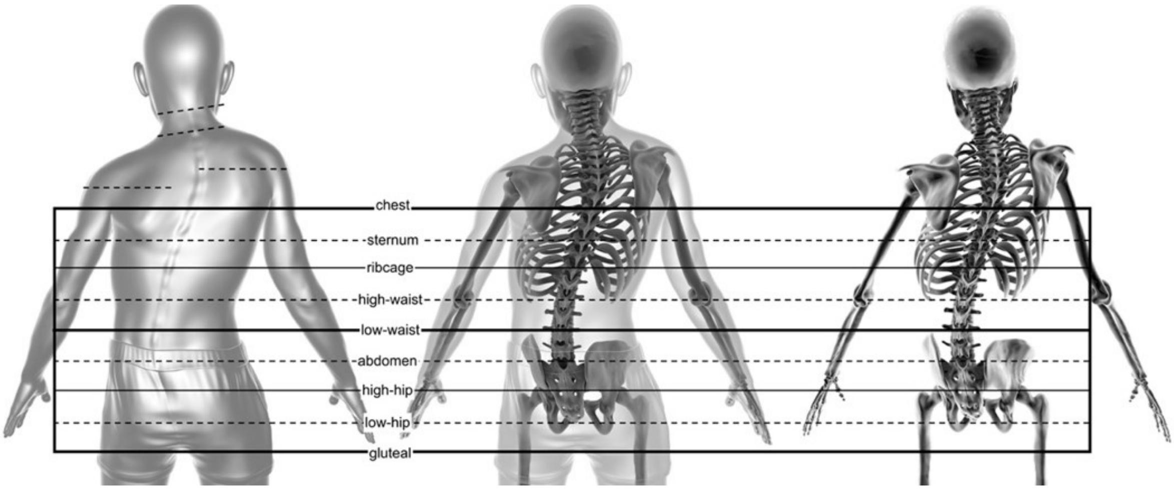


Fig. 5 Assignment of key girths to a scoliotic body-shape.

L&M theory must, as much as possible, also support the accommodation of outlier and even extreme deformities if goals of mass customization are ever to be achieved. Product development for scoliotic body shapes has had limited yet sufficient research to demonstrate the possibility of a direct humanoid-to-coveroid process [38,39]. The proportional division discussed herein shows further promise toward these efforts. Further study of tissue-to-skeletal interaction could direct improvements here [40].

3.3 Assign non-stable morphological landmarks driving artisanal technique

The use of proportional division may evoke concerns regarding the change management of traditionally assigned girths. As the waist is both a key size chart girth and critical apparel design line, this girth will be of significant concern. As illustrated in Figure 3, our research suggests the use of two cross-sectional waist girth planes (high and low waist) sufficiently identifies the area identified in ISO 18825 as the waist area. Cross-population variation noted with skeletal location of these landmarks can be attributed to expected discrepancy in vertebra spacing. From a design perspective, percentage division provides superior data. Understanding the low-waist to be positioned at the midpoint (50%) between chest and gluteal and the high-waist to be at 37.5% of the distance from chest to gluteal provides vital data regarding proportion and balance. Morphological assignment of waist, while well suited to bespoke apparel design, has little value in a ready-to-wear environment where decisions regarding proportion and balance are firmly established within the apparel production pattern (unassembled coveroid). Its value for size selection is even less because here again, the position of the waist has already been established within the coveroid. Toward optimal size selection, the comparison of proportional girths offers superior fit analysis data regarding lengths and girths for comparison against size chart dimensions.

Another heuristic activity in the fit of coveroids is the act of fitting angled design lines. Figure 6 illustrates the allocation of a tilted waist to accommodate pelvic tilt. Where heuristic practice understands a waist band is being angled to accommodate pelvic tilt, a geometrically constrained body-to-pattern perspective proves this argument false. Pattern-engineering is founded on principles of draping and the understanding that the base position for fabric on the body is regarding a vertical body center plane [35]. Even with bias fabric grain (fabric at 45° to the body center), the vertical body center plane is the base reference point. Consequently, regardless of pelvic tilt, fabric wraps around the body with reference to the body center. While heuristic logic directs us to measure from an angled waist, geometric constrained logic infers this relationship from transverse planes. Figure 6 illustrates the assignment of a tilted waist with geometric constraints for the derived size chart girths (thick line at the waist). From a production perspective, geometrically assigning an angled waist is a far more viable option than hand-locating unique morphology on potential customers.

Hence, the suggested L&M strategy avoids change management by permitting traditional physical-space practice to exist within digital-space practice. Where traditional practice says place a design line at the smallest girth and name this girth the waist, conscious design says place a design line at a position on the torso (e.g., 37.5% of the distance from chest to gluteal). The former is heuristic practice not well suited to digital environments while the latter supports DPC. Further validation studies should confirm this theory closely matches the girths referenced in ISO standards.

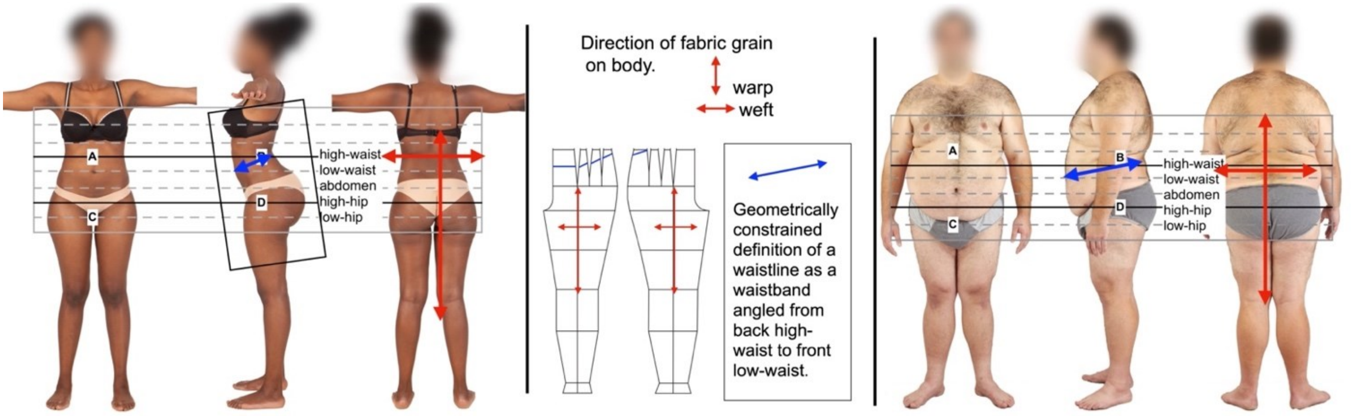


Fig. 6 Planar versus non-planar cross-sectional girths.

3.4 Derive humanoid rigging landmarks

The humanoid animation (HAnim) architecture for modeling the virtual skeleton (rig) is organized into a joint, segment, and site hierarchy. Joints connect segments which are understood to be virtual bones. Any sub-division of a bone is understood to be a site. Since the virtual skeleton is merely a simplified 'stick' version of a human skeleton, displacers radiate from joint and site locations to suggest body widths and depths (dimensions and shape) and to create an interface between the skeleton and humanoid mesh (skin). The bone-to-mesh attachment point consists of a displacer connecting a joint or site to a point on the mesh referred to as a weight point. Weighting assigns soft physics properties to the humanoid surface (mesh), thereby defining the realism an animated humanoid will exhibit [41]. Points may be weighted from zero, indicating a surface is entirely malleable, to 100%, indicating the surface is hard. For example, since no point on the body is either completely malleable or completely hard, a breast point may have a weight of 20%, while an elbow point may have a weight of 90%.

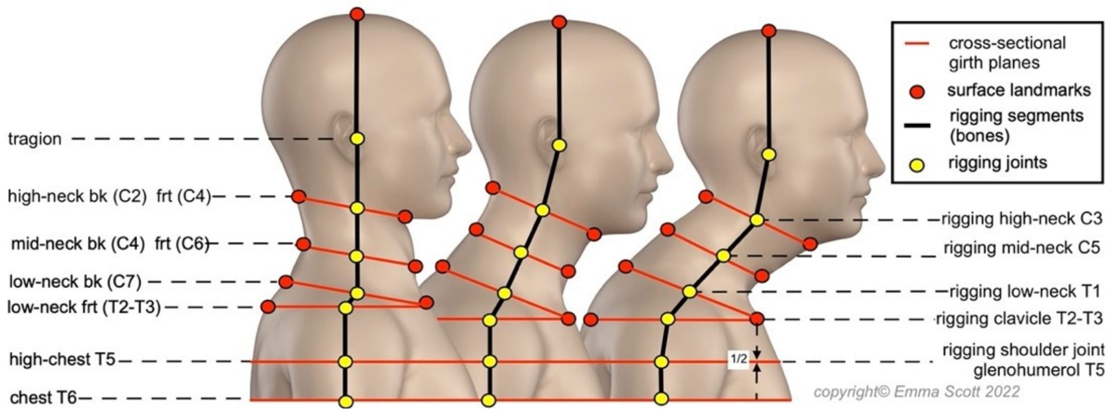


Fig. 7 Skeletal versus surface neck landmarks.

The neck and shoulder areas are particularly complex due to the need to account for multiple possible spinal variations. A review of this area found challenges with correctly modeling even minor spinal deformities (such as that occurring with age-related rounding of the shoulders) suitable for critical fit assessment [4]. Due to the complex interplay of the neck with the clavicle and scapula bones, our suggested rig includes four neck joints to better accommodate the upper back curvature possible with thoracic kyphosis. Figure 7 illustrates the complexities of modeling the neck. Surface landmarks on the humanoid direct the virtual skeleton (rig). However, due to the angled cross-sectional planes created by connecting the front and back surface landmarks, the rigging neck landmarks are essentially averages of the front and back mesh feature points. For example, the rigging low-neck landmark is located at first thoracic vertebrae (T1) which is an averaged position between the clavicles and seventh cervical vertebrae (C7) skeletal landmarks.

4 Weighting for improved humanoid parameterization

Traditional placement of landmarks, while eminently necessary for aesthetic design decisions, has proven a significant hurdle for selling apparel products and, indeed, a roadblock for 3D technologies. Here we have recommended morphological assignment of key girths be replaced with proportional division but this in no way negates the importance of unique morphological landmarks. As discussed, weights, via displacers, connect feature points on the humanoid surface morphology (skin) to joints or sites on the bone segments. Therefore, by assigning morphological landmarks as weight points traditional practice may exist within evolved practice. For example, traditional waist and hip (letters in Fig. 3) can be assigned with reference to the proportionally assigned waist and hip, as a distance above or below. Hence, traditional practice may exist within practice better suited to digital environments via the use of weighting points connecting unique morphology, perhaps a preferred waistband location, to a skeletal globally relevant waist.

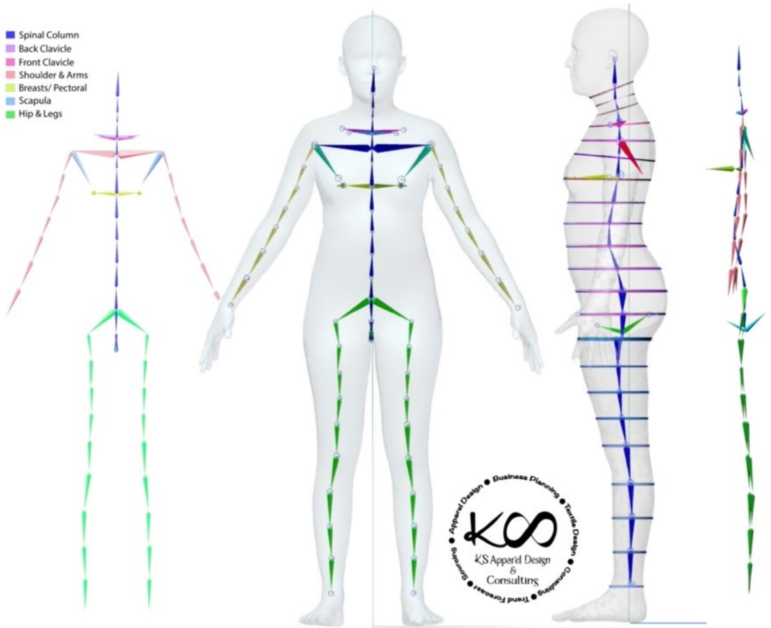


Fig. 8 Humanoid rig derived from Clone Block™ L&M.

The interconnectedness of the humanoid skin and virtual skeleton permits the modeling of the complex interplay between skin, tissue, and bone understood to be human movement. It also presents a means by which current twinned approximations of body-shape may evolve for a cloning of morphology. Current methods of inferring human morphology from limited body dimensions (bust, waist, and hip), while appearing realistic, frequently result in inaccurate distribution of weight [40,42] and have been found to be unsuitable for critical fit assessment [43,44]. Here we speculate that the suggested extensive cross-sectional girths coupled with the use of caliper width and depth sub-division of cross-sectional planes, will improve the distribution of body weight (left-to-right and front-to-back) understood to be body-shape. Further study should explore the use of the L&M suggested herein as a means for a more thorough weighting of skin to bone resulting in improved parametric humanoids.

5 Summary

For virtual fit testing it is imperative that surface landmarks ISO/IEC 19774-1:2019-Part 1: Humanoid animation (HAnim) architecture offers several suggested levels of articulation (LOA) for building humanoid rigs for animation [20]. HAnim LOA2 offers insufficient landmarking detail to drive a direct relationship between the humanoid and coveroid. LOA3, while offering extensive detail, lacks some of the key landmarks detailed in Appendix 2. Figure 8 illustrates a rig derived from Clone Block™ L&M which rests somewhere between existing standards.

The use of Clone Block™ L&M for rigging practice was previously reviewed in the paper "Relationships Between Rigs and Humanoid and Coveroid Landmarks" and found beneficial [4]. Confirmation that this practice suits production environments will follow this study. The usefullness of the suggested Global Standardized L&M for normalizing cross-population length variability and improving 3DBP interoperability will be focusses of a followup study. If agreed satisfactory, the inclusion of this methodology in ISO standards directed at apparel digitazation will be recommended.

6 Conclusion

Digital product creation has substantial roadblocks all pointing back to the need for globally recognized standardized L&M: inaccurate parameterization of humanoids, rigs, challenges with fit validation and prediction. Sustainability initiatives, focused on reducing garment returns, are hampered by landmarking and measuring practice leading to the comparison of cross-sectional planes (size chart girths) at different skeletal heights. Further, with current study demonstrating the necessity for accurate humanoid soft body physics to achieve a realistic simulation of the humanoid-to-coveroid interaction [41], the need to begin with an accurate body model is paramount. The need for change within established apparel practice is urgent [10,55,56]. Global Standardized landmarking and measuring is central to this change.

Here we propose a means for traditional L&M practice to exist within an evolved practice (Clone Block™ L&M) better suited to digital environments and better suited to comparison of unique morphology across widely varying population data. With study suggesting the urgent need for global standardization (see Appendix 1), further study to validate and refine the findings here could provide a path forward for widespread adoption of 3DBP technologies and improved size chart methodologies. Evolved global standardized L&M should address the following urgent challenges:

- critical fit assessment reducing garment returns while accommodating global demographics;
- 4D study and solving known challenges with polygon division for mesh segmentation on the homologous mesh [41];
- improving the accuracy of parametric humanoids that often display unrealistic body-shape [42];
- improving the results of archived demographic data, possibly in error due to the random assignment of morphological landmarks and mismatched cross-sectional planes;
- Theory suitable for all humans and therefore agnostic of gender, age, and height.

Author Contributions

E. Scott: theory and author, literature review, editing, figures, and tables; K. Schildmeyer: discussion, test rigging validation; S. Ashdown: discussion, editing, and review; G. Ruderman: discussion, editing, and review; C. McDonald: discussion, test rigging validation; S. Gill: discussion. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

Emma Scott is developing software utilizing Clone Block™ theory.

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Appendix 1 – Quotes supporting urgent need for L&M standardization.

Ref.	Year	Quote
[8]	AHMED et al. (2019)	“Progress regarding the definition of landmarking may permit the mitigation of some potential inaccuracy. In which case, the definitions for landmarks and measurements will become similar for both manual and scanner methods.”
[45]	Gill et al. (2018)	“… some measurements which were required or identified as important could not be created…This highlights the potential difference between the scan defined measurement locations and the marked locations on dress forms and suggests a clear need to consider this in research.”
[46]	Daanen & Psikuta (2018)	“Reducing the 3D scan to 1D-derived body dimensions is not using the full potential of 3D body scanning. Processing the data in 3D will give more and more detailed information on the body.”
[6]	Gill et al. (2014)	“… until there are clear and detailed methods for all applications requiring waist measurements the definition of the waist will remain an area of potential contention.”
[47]	Verweijet al. (2013)	“… for accurately monitoring changes in waist circumference of individual subjects over time … consensus is needed on adopting a uniform protocol for measuring waist circumference.”
[28]	Han & Nam (2011)	“Standard landmark identification methods, including ISO 8559 (ISO 8559, 1989), are somewhat ambiguous when applied geometrically to 3D body scans.”
[48]	Strydom & De Klerk (2010)	“For more than half (58.8%) of the key dimensions, the respondents did not agree on the description of how and/or where the measurement should be taken. … For consistency in sizing it is also important that the key dimensions be measured in a standardized way by all manufacturers and retailers.”
[49]	Ashdown & Na (2008)	“Finding the landmarks on the scans of the older individuals was generally more difficult than finding the landmarks on the scans of the younger individuals because some of the older participants had experienced body shape changes that affected the areas where landmarks were located.”
[50]	Labat & Delong (2006)	“There have been considerable advances in the variety and accuracy of methods to take body measurements, but we continue to struggle with the relationships and applications to garments. Even into the 21st century we have not achieved the goal of providing the same quality of fit for “every body.” Instead, we have dismissed the unique body and expect all bodies to fit into standard-sized garments. The unfortunate result is that we have come to expect the human body to match the clothing standard rather than develop clothing to fit each human body.”
[51]	Simmons & Istook (2004)	“Regardless of how one defines fit exactly, it must always start from basic human proportional truths.”
[52]	Simmons & Istook (2003)	“… how each scanner establishes landmarks and takes the measurements should be established so that standardization of the data capture can be realized… Until the data capture process of specific body measurements can be standardized or communicated among scanning systems, this island of technology cannot be utilized for its maximum benefit within the apparel industry.”

Appendix 2 – Proposed Landmarking for Global Standardized Measuring Practice

Stable Landmarks, Automated Landmarks, Derived Landmarks, ***Rig Specific Landmarks***

		FEATURE POINTS (relevant to Global Standardized Apparel L&M)	Virtual bones (segments) require an upper (left) and lower (right) joint.	FEATURE POINTS relevant to Global Standardized Hanim & Rigging L&M)
Head	1	head vertex		*points weighted to tragion*
	2	head back (opisthocranion)		
	3	brow center (glabella)		
	4	head joint (tragions)	*bone head*	*rigging high-neck (C2 - derived)*
Neck	5	back high-neck (C1)		*points weighted to skeletal high-neck*
	6	front high-neck (C3)		
	-	*rigging high-neck (C2 - derived)*	*bone neck #1*	*rigging mid-neck (C5)*
	7	back mid-neck (C4)		*points weighted to skeletal mid-neck*
	8	front mid-neck (C6 Adam's Apple)		
	-	*rigging mid-neck (C5)*	*bone neck #2*	*rigging low-neck (T1 - derived)*
	9	clavicles		*points weighted to skeletal low-neck*
	10	front low-neck (T2 - derived)		
	11	back low-neck (C7)		
	12	side neck (rigging low-neck)		
	-	*rigging low-neck (T1 - derived)*	*bone spine #1*	*rigging clavicle*
Torso	-	*rigging clavicle*	*bone spine #2*	high-chest/ glenohumeral (T4-T5 midpoint between clavicles & axilla)
	13	high-chest/ glenohumeral (T4-T5 midpoint between clavicles & axilla)	*bone spine #3*	chest (T6-T7 - derived from axilla)
	14	chest (T6-T7 - derived from axilla)	*bone spine #4*	sternum spine (T9 -12.5% chest-gluteal)
	15	sternum spine (T9 -12.5% chest-gluteal)	*bone spine #5*	ribcage (T11 - 25% chest-gluteal)
	16	ribcage (T11 - 25% chest-gluteal)	*bone spine #6*	high-waist (L1-L3 - 37.5% chest-gluteal)
	17	high-waist (L1-L3 - 37.5% chest-gluteal)	*bone spine #7*	low-waist (L3-L5/ ilium - 50% chest-gluteal)
	18	low-waist (L3-L5/ ilium - 50% chest-gluteal)	*bone spine #8*	abdomen (S1 - 67.5% chest-gluteal)
	19	abdomen (S1 - 67.5% chest-gluteal)	*bone spine #9*	high-hip (root - 75% chest-gluteal)
	20	high-hip (root - 75% chest-gluteal)	*bone pelvis side (2)*	low-hip (femur joint - 87.5% chest-gluteal)
	-	high-hip (root - 75% chest-gluteal)	*bone pelvis center*	low-hip (femur joint - 87.5% chest-gluteal)
	21	low-hip (femur joint - 87.5% chest-gluteal)	*bone upper leg (2)*	knee (patella)
	22	gluteal		*points weighted to low-hip*
	23	crotch (perineum 1/2 caliper highthigh)		
Leg	24	high-thigh (average of gluteal points)		*site on upper leg bone*

	25	mid-thigh (25% gluteal-knee)		
	26	low-thigh (50% gluteal-knee)		
	27	high-knee (75% gluteal-knee)		
	28	knee (patella)	*bone lower leg (2)*	ankle (lateral malleolus)
	29	high-calf (25% knee-ankle)		
	30	mid-calf (50% knee-ankle)		*site on lower leg bone*
	31	low-calf (75% knee-ankle)		
	32	ankle (lateral malleolus)		-
Foot	33	floor/ heel landing point	*bone foot #1 (2)*	ankle (lateral malleolus)
	34	heel (calcaneus_posterior)	*bone back foot #2 (2)*	ankle (lateral malleolus)
	35	foot bridge		*points weighted to to ankle*
	36	longest toe (tarsal_distal_phalanx)	*bone front foot #3 (2)*	ankle (lateral malleolus)
Shoulder	37	upper scapula point	*bone upper scapula (2)*	*rigging clavicle*
	-	*rigging mid-shoulder*	*bone clavicle (2)*	*rigging clavicle*
	38	lower scapula point	*bone lower scapula (2)*	*glenohumeral (T4-T5)*
	-	*glenohumeral (T4-T5)*	*shoulder bone (2)*	*high-chest/ glenohumeral (T4-T5 midpoint between clavicles & axilla)*
Arm	39	acromion (T3)		
	40	front axilla (T6)		*points weighted to glenohumeral*
	41	back axilla (T7)		
	42	underarm (T8 1/2 caliper)		
	-	high-chest/ glenohumeral (T4-T5 midpoint between clavicles & axilla)	*bone upper arm (2)*	elbow
	43	biceps-high (33% underarm-elbow)		*site on bone upper arm*
	44	biceps-low (66% underarm-elbow)		
	45	elbow	*bone lower arm (2)*	wrist (ulna stylion)
	46	forearm-high (33% elbow-wrist)		*site on bone lower arm*
	47	forearm-low (66% elbow-wrist)		
	48	wrist (ulna stylion)	-	-
Hand	-	wrist (ulna stylion)	*bone upper hand (2)*	mid finger root
	49	mid finger root	*bone lower hand (2)*	pinky root
	50	pinky root		-
	51	thumb root	*hand width bone*	mid finger tip
	52	mid finger tip		-
Breast	-	sternum spine (T9 -12.5% chest-gluteal)	*bone pectoral (2)*	*rigging apex*
	53	inner inframammary fold (2)		
	54	apex / thelion (T8-T10)		
	55	outer breast		*points weighted to rigging apex*
	56	upper breast		
	57	lower inframammary fold		

Appendix 3 – Automated Landmarks required for Global Standardized Measuring Practice

Clone Block™ Landmarking and Measuring for 3DBP Interoperability

(Required feature points for apparel 4D study)

ISO 8559-1:2017	**ISO 7250-1:2017**	**ISO 18825-2-2016**	**ISO / IEC 19774-1: 2019**		Left / right	Stable		Automated Extraction Algorithms Required *(Note the left/right column indicating where 2 points are required.)*
	5.2	2.1.1	0	Head	na	✓	1	head vertex
	5.1	NEW	89		na	✓	2	head back (opisthocranion)
3.12	5.6	4.1.2 (#1)	1		na	✓	3	brow center (glabella)
3.13	5.20	4.1.2 (#6)	81		✓	✓	4	head joint (tragions)
	5.9	4.1.2 (#10)	***NEW***	Neck	na	✓	5	front high-neck (C3)
3.18		2.1.3	14, 12		✓	✓	6	clavicles
3.16	5.3	2.1.5	10		na	✓	7	back low-neck (C7)
3.1.26		2.2.20	***NEW***	Leg	✓	✓	8	gluteal
	5.4	*2.1.16*	*38*		*na*	*na*	*9*	*crotch (perineum 1/2 caliper highthigh)*
3.1.17	5.2	2.1.22	45,41		✓	✓	10	knee (patella)
3.1.18		2.1.25	49,53		✓	✓	11	ankle (lateral malleolus)
		21.26	***NEW***	Foot	✓	✓	12	floor/ heel landing point
			58,62		✓	✓	13	heel (calcaneus_posterior)
			115,120		✓	✓	14	longest toe (tarsal_distal_phalanx)
3.1.11	5.2	2.1.10	31, 29	Breast	✓	na	15	apex / thelion (T8-T10)
3.1.20		2.1.11	***NEW***		✓	na	16	lower inframammary fold
3.1.1	*5.2*	*2.1.6*	*15,20*	Arm	*✓*	*✓*	*17*	*acromion (T3)*
3.1.13		2.1.8	17,22		✓	✓	18	front axilla (T6)
3.1.14		2.1.9	16, 21		✓	✓	19	back axilla (T7)
		2.1.7	*18,23*		✓	*na*	*20*	*underarm (T8 1/2 caliper)*
3.1.10	5.1	2.1.17	65, 68		✓	✓	21	elbow
3.1.19	5.2	2.1.18	70, 73		✓	✓	22	wrist (ulna stylion)
		mid finger root	76, 79	Hand	✓	✓	23	mid finger root
		pinky root	77, 80		✓	✓	24	pinky root
		thumb root	75, 78		✓	✓	25	thumb root
		2.1.19	103, 108		✓	✓	26	mid finger tip