COMMUNICATIONS IN
DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Skin and soft tissue modeling and its impact on apparel modeling

Randy K. Rannow[1,*], Carol McDonald[2,*], Alfredo Ballester[3], Katy Schildmeyer[4], Emma Scott[5], Simeon Gill[6]

[1] *Silverdraft Supercomputing, Boise, ID, USA*
[2] *Gneiss Concept, Washougal, WA, USA*
[3] *Instituto de Biomecánica de Valencia (IBV), Universitat Politècnica de València, Spain*
[4] *KS Apparel Design, Salt Lake City, UT, USA*
[5] *Fashion Should Empower, BC, Canada*
[6] *University of Manchester, Manchester, England, UK*
* Corresponding author *E-mail addresses:* pi-boson@ieee.org (R.K.R.), carol@gneissconcept.com (C.MD.)

INFO

CDAPT, ISSN 2701-939X
Peer reviewed article
2023, Vol. 4, No. 2, pp. 151-163
DOI 10.25367/cdatp.2022.4.p151-163
Received: 06 January 2023
Accepted: 05 April 2023
Available online: 07 May 2023

ABSTRACT

Rigid body avatars do not fully define the complex interaction between human and body-worn product (humanoid-to-coveroid). Skin and soft tissue modeling to create more realistic 3D humanoid body models are needed. We considered if humanoid split lines relevant to pattern-engineering practice can be related to biodynamic and fold lines of the skin. Changes in skin and tissue are expected, depending on the dermis, the effects of movement, and the effects of coveroid pressure. The physiological functions of the skin may be assigned mechanical parameters for dynamic study utilizing biodynamic excisional skin tension (BEST) lines, main folding lines (MFL) with Langer's lines. Critical to such study is the connecting of the skin to the rig (humanoid virtual skeleton). The use of stable (skeletal feature points related to both the virtual skeleton and apparel block patterns) and morphological (skin feature points identifying areas of morphological variation and dynamic study) landmarks for connecting the skin to rig was analyzed. We utilized these landmarks to drive lines as BEST, MFL and Langer's lines for the mapping of skin deformations. Initial findings suggest the use of stable and morphological landmarks could have profoundly positive effects throughout the entire digital product creation (DPC) production pipeline and should be further explored & are important in developing standard topology practice.

Keywords
landmarking,
feature points,
rig,
soft tissue modelling,
2D modeling

1 Introduction

The human skin is the largest organ in the human body, a complex, multi-layered material broadly divided into three layers: epidermis, dermis, and hypodermis. The human skin surface acts as a semi-permeable membrane interacting with the human immune system, as well as the outer environment [1]. The mechanical attributes of human skin are important for a number of applications (medical, forensic science, art & entertainment, biomechanics, life sciences etc.), especially with the more recent advent of the digital twin.

Apparel comfort is a key attribute for desirable clothing. While there has been considerable work in comfort perception, when it comes to the use of technology (e.g., 3D human scanning), there may be the perception that fit, or garment design may not be realized. It may be that the requirements or expectations of consumers are changing, along with products and wear situations. In a highly competitive textile and apparel market, in order to succeed in the market, apparel vendors must consistently exceed consumers' needs and expectations, and understanding the human-clothing interaction, and how technology may be an enabler.

Rigid body avatars do not fully define the complex interaction between human and body-worn product (humanoid-to-coveroid). Traditionally used pressure maps while useful in defining 'tightness' on the rigid body humanoid, are not reflective of the dynamic nature of human skin. Pressure maps do not consider the elastic limits of skin or the compressibility of soft tissue [2]. Skin and soft tissue modeling to create more realistic 3D humanoid body models are needed. The compression of clothing on the humanoid is more correctly modeled on soft tissue humanoids (soft tissue layer or modeling soft tissue dynamics) but the mapping of skin deformations remains very complex and computationally intense. To make these methods useful for pattern-engineers, simplified methods relevant to apparel production are needed. Here we considered if humanoid split lines relevant to pattern-engineering practice can be related to biodynamic lines of the skin. Basically, adjusting the approach to current topology based on purpose of the form.

The physiological functions of the skin may be assigned mechanical parameters for dynamic study utilizing biodynamic excisional skin tension (BEST) lines [3] and main folding lines (MFL) [4] of the skin. Critical to such study is the connecting of the skin to the rig (humanoid virtual skeleton). Toward this, we explored the use of stable (skeletal feature points related to both the virtual skeleton and apparel block patterns) and morphological (skin feature points identifying areas of morphological variation and dynamic study) landmarks for connecting the skin to rig.

The primary paper "Proposed Landmarking for Improved Digital Product Creation" [5] identified the usefulness of stable and morphological landmarks as a cross-platform method for better identifying body regions areas thereby decreasing compounding measuring error. Here we utilized these landmarks to drive lines identifying body regions as BEST lines or MFLs for the mapping of skin deformations. Initial findings suggest the use of stable and morphological landmarks could have profoundly positive effects throughout the entire digital product creation (DPC) production pipeline (sampling to garment returns) and should be further explored as standards better suited to widespread adoption of 3D technologies. Such study facilitates an understanding of how malleable flesh on breasts, arms, abdomen, and thighs may be more accurately modeled and understood for a clearer understanding of the humanoid-to-coveroid interaction colloquially described as fit.

2 Human skin

Anthropometric human body imaging is used to obtain various data about human body and its physical properties, and generally categorized as static and dynamic measurements. Static data includes circumferences and lengths, as well as volumetric and the physical topology of the skin. Dynamic data link measurements and body landmark locations.

Young's Modulus (i.e., mechanical behavior of human skin) is measured as a ratio of the applied stress to the skin versus skin deformation, using in vivo or in vitro measurement methods. Experimental data assessing the Young’s Modulus of human skin may be influenced by a number of factors, including the location of the skin on the body and the underlying body structure and the tissue or bone underneath the skin in that location. Skin is found to be highly anisotropic and viscoelastic, with a range of Young’s Modulus between 5 kPa and 140 MPa, and it is the location on the body, as well as the Young’s Modulus of location-specific skin that influences how apparel or material may contact the body, along with the individual's sensory response [6]. That is, the mechanical response of the skin is influenced by movement, such as stretching (tensile) or normal load (indentation), as well as by rotation or movement that results in the epidermis seeing varying torsional loads. Furthermore, structural properties of the human skin influences the experience of apparel, relative to the human body. The human skin varies from 0.5 mm to 4 mm thick, depending on the location of the skin on the body, and consists of the epidermis, dermis and hypodermis as shown in Figure 1. Collagen fibers in the dermis are primarily responsible for the load-carrying response of the external surface of the epidermis structure, which influences how apparel or material contacts the body. The mechanical and structural response of the human skin, as well as the variance of the human body influence the ability to get accurate and repeatable measurements.

Furthermore, Young’s Modulus of skin is an important factor to estimate the characteristics of skin and the mechanical behavior of the skin which may influence one's physical perception of comfort (i.e., ease, fit, etc.). Understanding Young’s Modulus of human skin may assist in calibrating the elasticity of apparel, relative to the person, to enable greater insight into skin-stretch induced motion artifacts and the comfort one experiences with apparel.

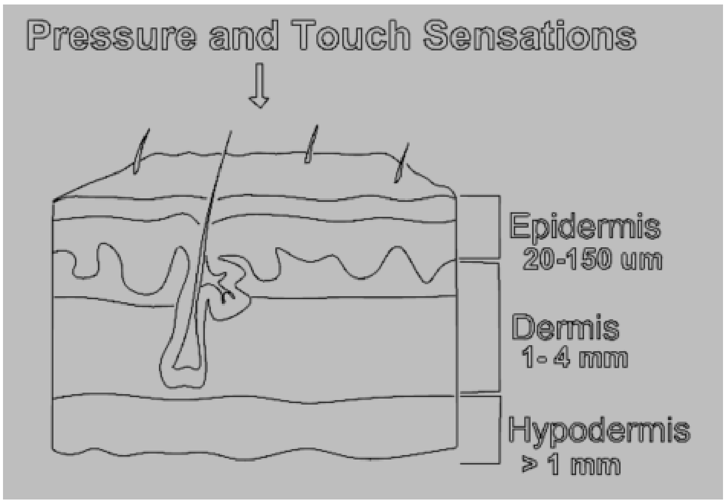


Fig. 1 Schematic of the human skin.

3 Anthropometry

There are a growing number of opportunities for vision or imaging-based anthropometry. Recovering 3D human body details for these application continues as the task of accurate anthropometric body measurements and body detail estimations, sufficiently detailed, is problematic due to the non-rigid model fitting procedures as absolute or relative vertex positions may greatly deformed. Thus, the vagaries of reference points (i.e., landmarks) may not align. That is, landmark locations along the contour of the body may result in circumferential path vagaries. Furthermore, landmarks may be influenced by fitting deformation. In order to provide more accurate anthropometric measurements, we propose a method of measurement that aligns the body mesh.

4 Landmarks

Stable landmarks are defined as landmarks that are related to the skeleton and not to the soft tissue of the body. The stable landmarks, shown in Figure 2, were also shown in the primary paper [5]. These are defined in a combination of the two ISO standards related to the digital avatar or humanoid. The ISO standards are: ISO 18825-2:2016 *Clothing – Digital fittings – Part 2 Vocabulary and terminology used for* *attributes of the virtual body* [7] and ISO 19774-1:2019, *Information technology – Computer graphics, image processing and environmental data representation – Part 1: Humanoid animation (HAnim) architecture* [8]. As these standards come from two very different fields of Apparel and Computer Science, the combination will be helpful for the 3D modeling in Apparel.

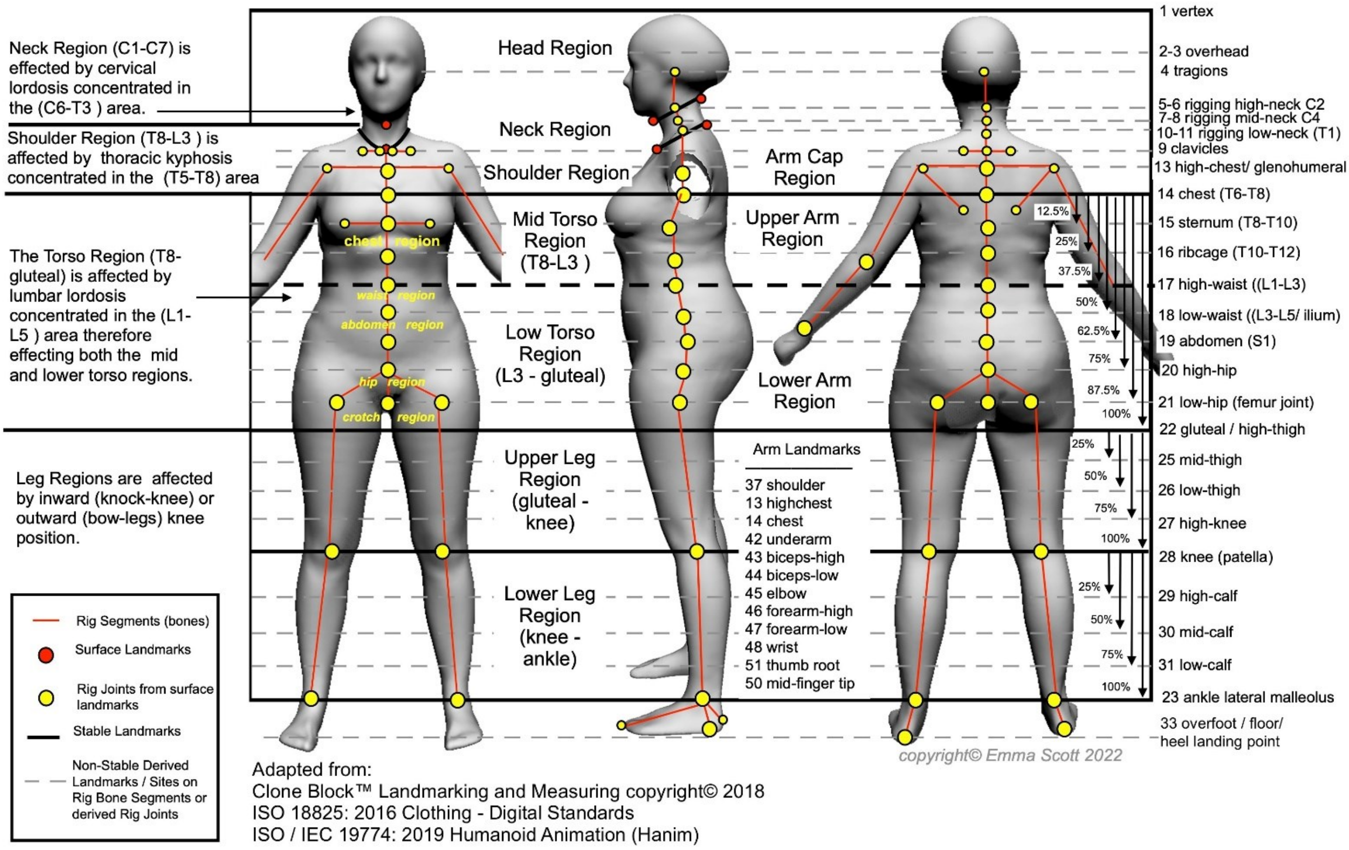
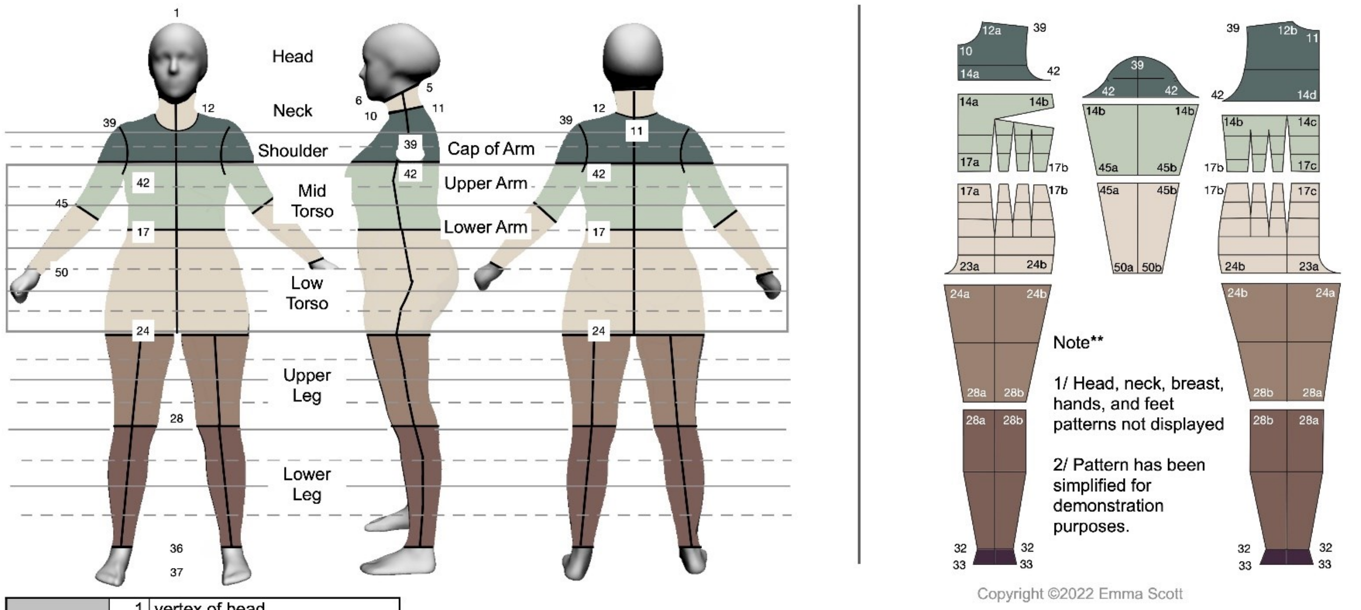


Fig. 2 Percentage Division of Known Body Regions for 4D Apparel Fit Study from Scott [5], used with permission.

The definitions of Landmarks are explained in detail in Landmarking paper from IEEE 3DBP Industry Connections website [9]. Table 5 explains regional landmarks from a mesh surface perspective as the body curve inflection points, percentages of caliper depths, girths, or apexes. The mesh surface landmarks related to the stable landmarks could help with location of the landmarks if one is using HAnim type of architecture or other methods for animation. Another paper that explains the impact of rigging for automation was presented at 3D Body Tech in 2022 [10]. If one has too few spinal joints or nodes for rigging, then the body's true movement or alignment cannot be generated. This impacts the correct garment modeling as the spinal curvature cannot be generated properly especially for older adults or anyone with asymmetrical spinal column. If one is compensating by the mesh shape instead of the neck or spinal rigging, the front of the body mesh may become inaccurate. The primary paper [5] explains in detail the proposed neck rigging and modeling.

The landmark regions identified in ISO 18825 are important for apparel fitting and help narrow down the location in which a landmark can be found. A simple example of this process for finding the location of landmarks: you will not find a neck landmark in the zone of the humanoid for the hip or waist.

The Landmarking to a body block shown in Figure 3 is an updated version from Landmarking paper [9] showing the 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. 3 Pattern to body regions relationship from Scott [5], used with permission.

5 Soft tissue impact

There are different causes for the soft-tissue deformation. It can deform because of muscle contraction, dynamic forces (gravity and inertia during motion), physical interaction with external objects (e.g. garments) and physical interaction from self-contacts of the body (e.g. at body folds, slits or limbs pressing/touching other body parts). The term "soft-tissue" is often used in literature to refer to a portion of the causes/effects of the actual soft-tissue deformation. In the current state of the art, generally, we find two approaches: modelling it or simulating it. The former typically considers soft-tissue deformation as a resulting surface mesh deformation from a pose/movement input. Within this group we find various skinning models (e.g., LBS, DQS or alike) and varying complex shape-pose models learnt from data using linear models [11] or more advanced approaches using deep learning models such as [12] or [13].

Such models can be extended to add dynamic forces [14] or self-contact awareness [15]. The latter approach, simulation, considers soft-tissue deformation as a result of an interaction of a human body with other objects (e.g., rigid objects, garment, seating, etc.) computed as a physical simulation using volumetric meshes (e.g., tetrahedral) [16]. These approaches are computationally more demanding than the models.

To create the effect of soft tissue, currently, animations, weighting deformers, and collusions, scripts applied to different morphs regions are required. It is the opinion of one of the authors that Skinned Multi-Person Linear (SMPL) [11] or Dynamic Human Shape in Motion called DYNA [14] are models that have had better success with soft tissue modeling against textiles as long as the compatible software is utilized, even though neither SMPL nor DYNA consider the interaction of garments within their models.

SPML model is a vertex-based model of which the parameters are learned from data from rest pose template, identity-dependent blend shapes and pose dependent blend shapes. The pose dependent blend shapes are a linear function of the elements of the pose rotation matrices. The DYNA model relates the linear coefficients of body surface deformation to the changing pose of the body. A second order auto-regressive model predicts soft-tissue deformations based on previous deformations and the velocity and acceleration of the body with movement.

A method described and patented by Casas D. et al. [13] [17] develops a neural network regressor that is trained on high-quality 4D scans from which pose, shape and soft-tissue information have been extracted. The regressor uses a nonlinear subspace containing an autoencoder to compact the soft-tissue dynamics information. The goal of this method is to plug into existing vertex-based methods for improved results and smaller computational overhead enabling real-time nonlinear regression to 3D animated sequences with skeleton.

Regarding the simulation approaches, the work by Pai, D. focuses on the localized impact of the garment and body interaction. This work included the mechanical characterization of human soft tissue using a proprietary device and to generate finite element modelling methods (FEM) to simulate soft tissue with contact and friction [16]. The company Vital Mechanics provides proprietary software to conduct simulations following these methods [18].

6 BioDynamic Excisional Skin Tension Lines, Main Fold Lines with Langer Lines

Bringing in the understanding of the skin from medical applications such as surgery to minimize scarring, may allow for better modeling of the skin during animation. In the 3D humanoid application, we do not need to worry about the impact to the patient, but we can use medical knowledge that has been in discussion since 1861. A history and review of skin lines are explained by Paul [3] along with detailed explanation of Langer’s lines (lines of tension in the skin due to collagen or “cleavage” lines). The Langer’s lines may not have to same anatomical pattern between people, or they are changeable even in the same person. As noted in paper [3], the skin will age along with the rest of the body as there is a degradation of the elastin fibers or increased viscoelastic behavior.

The ISO 19774 and its implementation using Web3D, X3D, require using a displacer node to link the movement of the skin to the joint centers. Understanding the skin lines allows for a better weighting of the skin movement. The term BioDynamic Excisional Skin Tension (BEST) lines was coined by Paul [19]. BioDynamic considers the tissues as 3D models, excisional is when a cut through the skin to remove a suspicious area and skin tension lines are the lines of mechanical tension in the skin as shown in Figure 4.

The Main Fold Lines (MFL) are where the skin folds and bends for movement and can be easily found by moving head or limbs on a real person and are shown in Figure 5 [4]. Facial MFL are not the focus of this paper. Using scanning methods such as MOVE4D (explained later in this paper) can help to determine MFL and skin movement for future machine learning databases especially in problematic areas of the body. Diagrams of the BEST lines and MFL are found in sources [19] and [4].

It is interesting to note that the BEST lines and MFL are either perpendicular to each other or at an angle for the arms and legs and yet the same orientation for the neck and torso. The BEST lines in the arms and legs are useful to model the skin in the extended position while the MFL lines are useful for the compressive position. For example, if one bends the wrist, the skin on one side of the joint will be in extension and the other side of the joint will be in compression. The side with extension can utilize the BEST lines for modeling skin behavior and the other side can use the MFL lines.

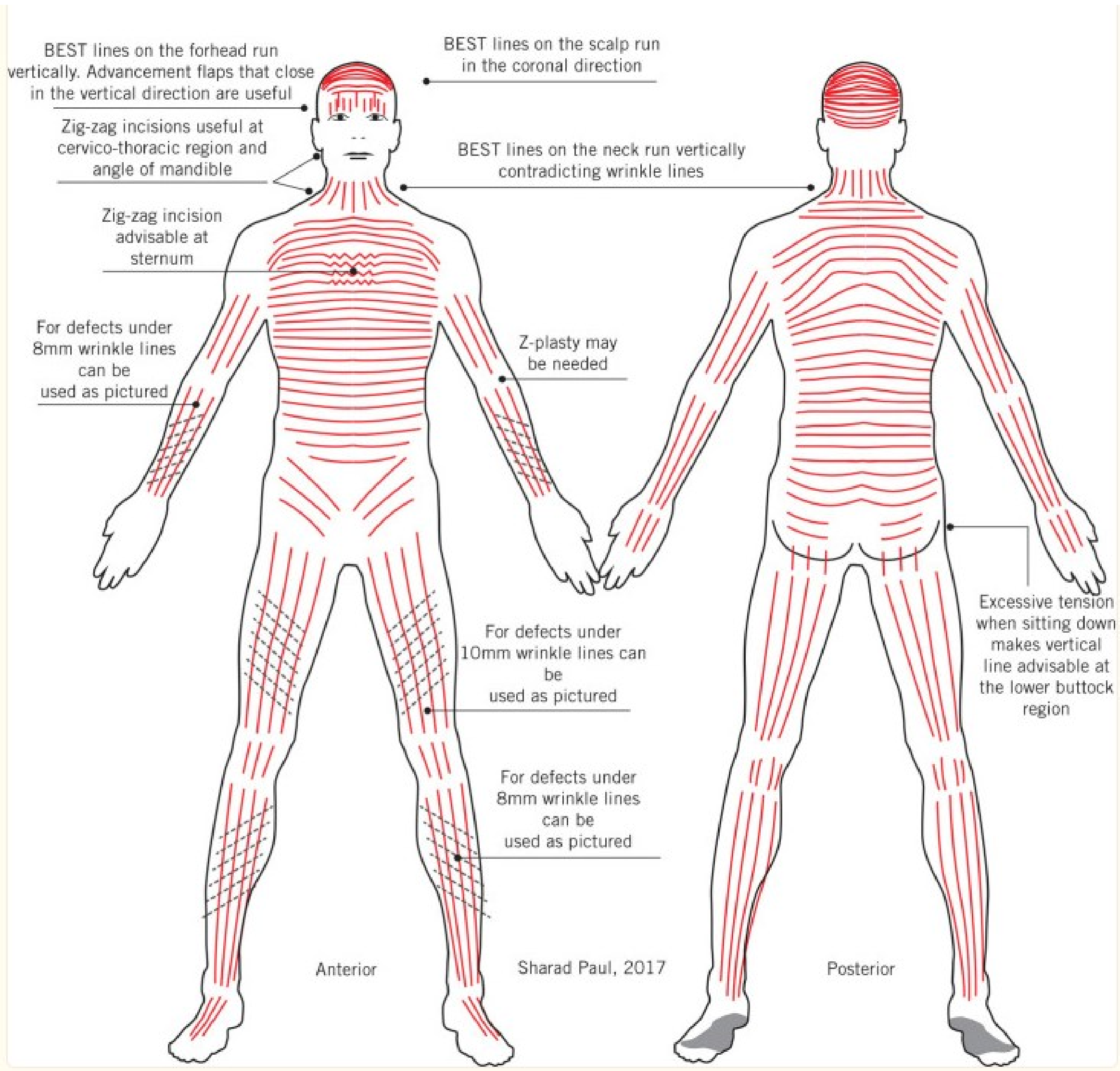


Fig. 4 BEST lines, a guide for excisional surgery, from Paul [19], used with permission.

Fig. 5 Recommended surgical incisions along main folding lines from Lemperle [4], used with permission.

7 Proposed solution

To overlay the landmarks specified with the BEST and MFL lines for modeling the skin behavior at the landmarks as shown in Figures 6 and Figure 7.

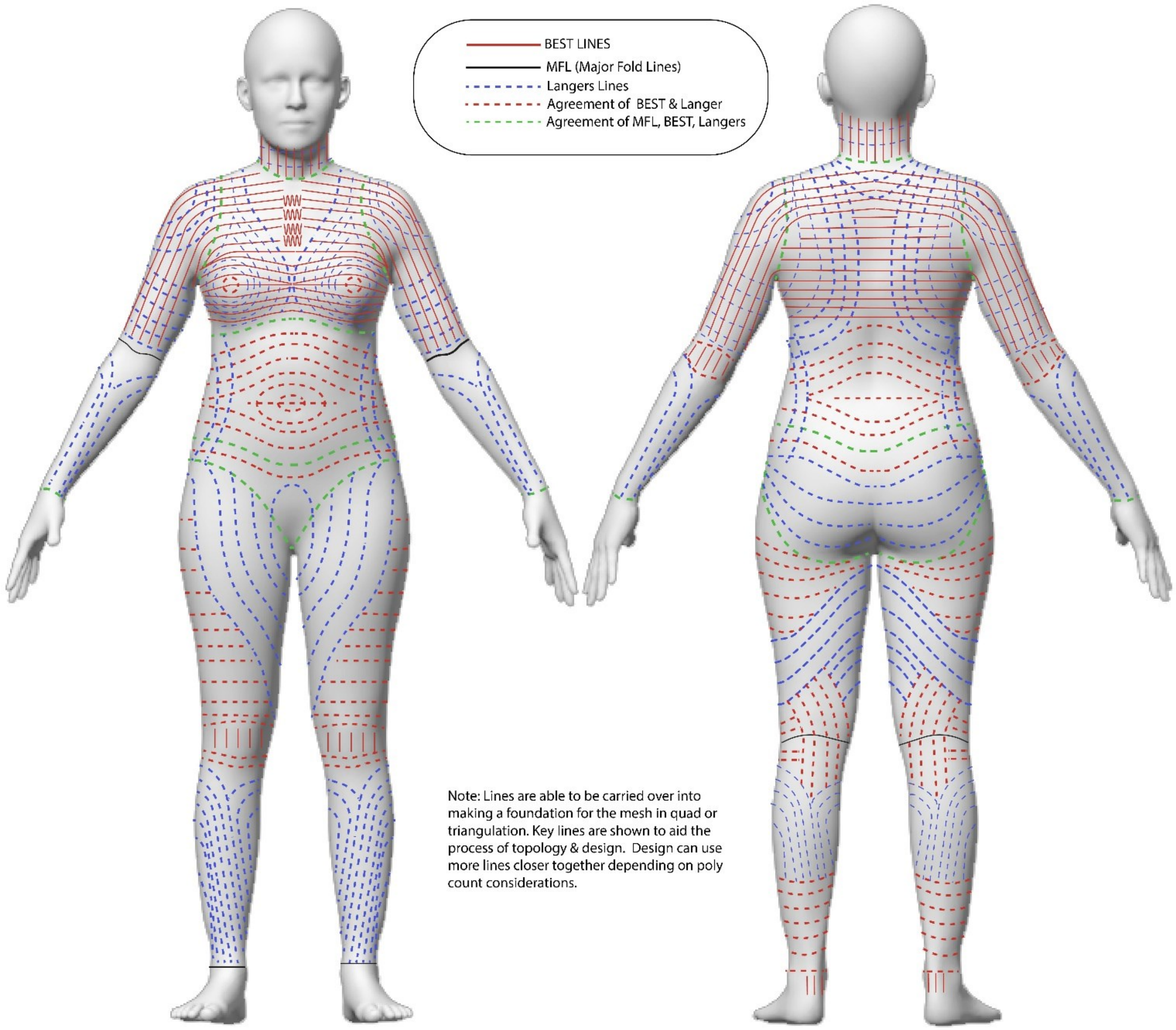


Fig. 6 BEST, MFL and Langer's lines.

Neither the BEST or MFL will help with defining the skin into quarters, Front – left, Front – right, Back – left and Back – right. However, if the body scan includes the skin texture, would that help with finding body features such as knees, elbows, and armpits, if the importing software can handle the texture layer.

Recognizing classification of the body may help in determining more complex areas of the body, such as the armpit (axilla) or crotch. These become key locations when any coveroid is separated to form a basis for a 2D cover for the 3D surface. These split lines are often consistent locations in constructing a pattern and require a clear relationship to anatomical structures to ensure they can be consistently applied to a population. Based on experience from one of the authors, each of type of lines (BEST, MFL and Langer) have a usage for skin modeling. For example, application of the BEST lines work well on the areas of tension within sternum, torso, buttocks, neck, and head. For the legs and arms, the BEST can be used for tension areas of elbow and knee. The MFL must be used for major joints or areas where the adipose fatty tissue can increase, like the low waist and high waist or under bust. Langer lines work best for use around the muscles in legs and arms. Mesh modeling would benefit from following the natural lines for muscle, MFL, and skin curvature. The topology could be extracted more effectively.

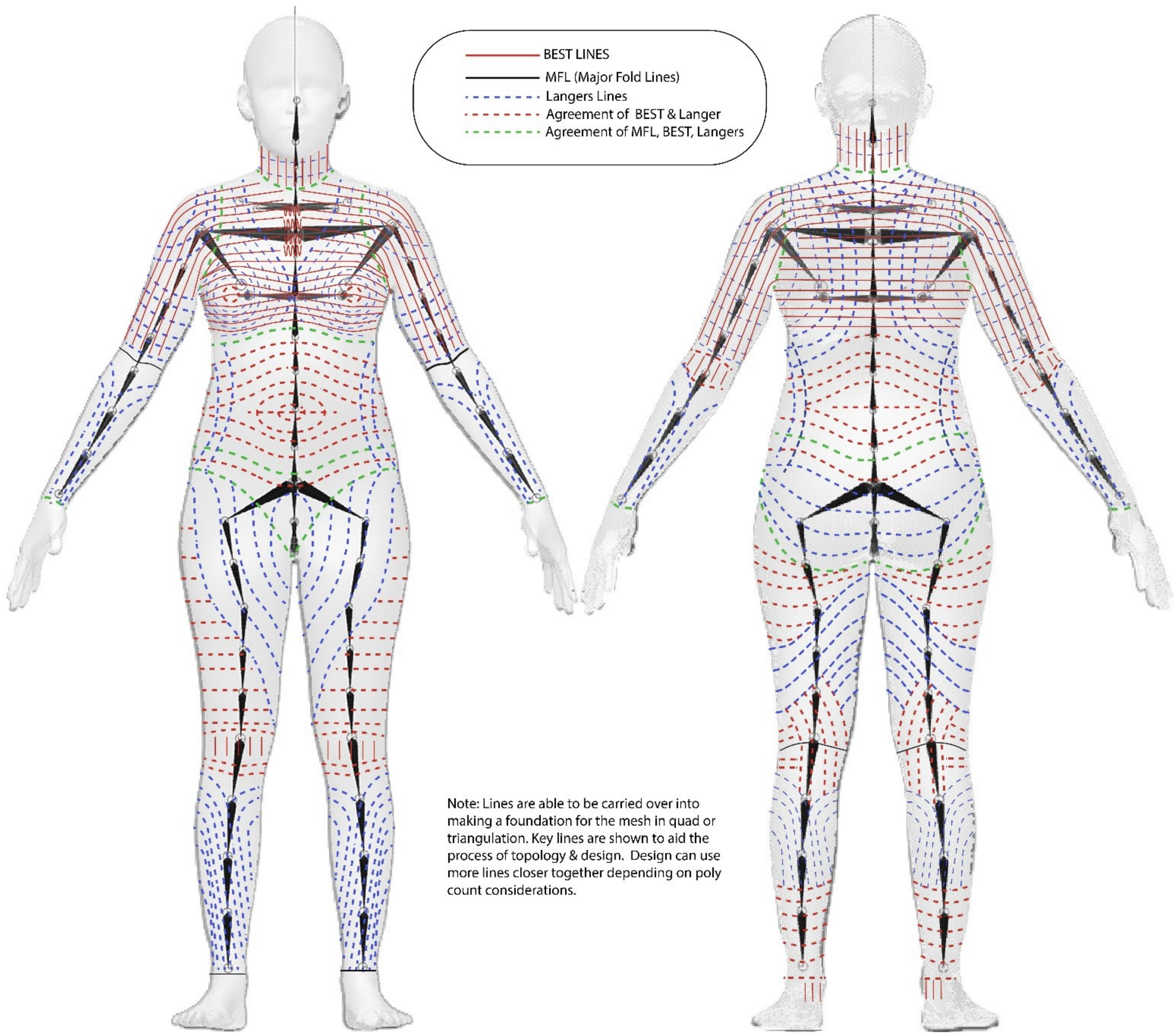


Fig. 7 BEST, MFL and Langer's lines with rig shown for reference.

The axilla creates a requirement for landmarks of the armpit at the front and back of the body, these define the armpit width, but also points to shape a sleeve and to aid division of an upper body block. The soft tissue points usually relate to a skin fold occurring below the joint of the pectorals to the humerus on the front and a similar location, often lower on the back where muscles join to the arm.

8 Current Practice for Skin Modeling

Figure 8 illustrates the use of a UV unwrapped mesh for an apparel production pattern. Here, the body region landmarks as illustrated in Figure 3 have been applied directly to the humanoid mesh to create split lines. The "bear skin", or flattened mesh, version of the human body is often portrayed as being suitable for making clothing patterns. While it is possible to split the mesh relative to planar lines on the body, the resulting pattern shape will lack nuances critical to pattern theory. For example, lines and curves must be trued smooth, shaping devices must be strategically inserted to correct fabric grain and reduce unintended wrinkling and buckling.

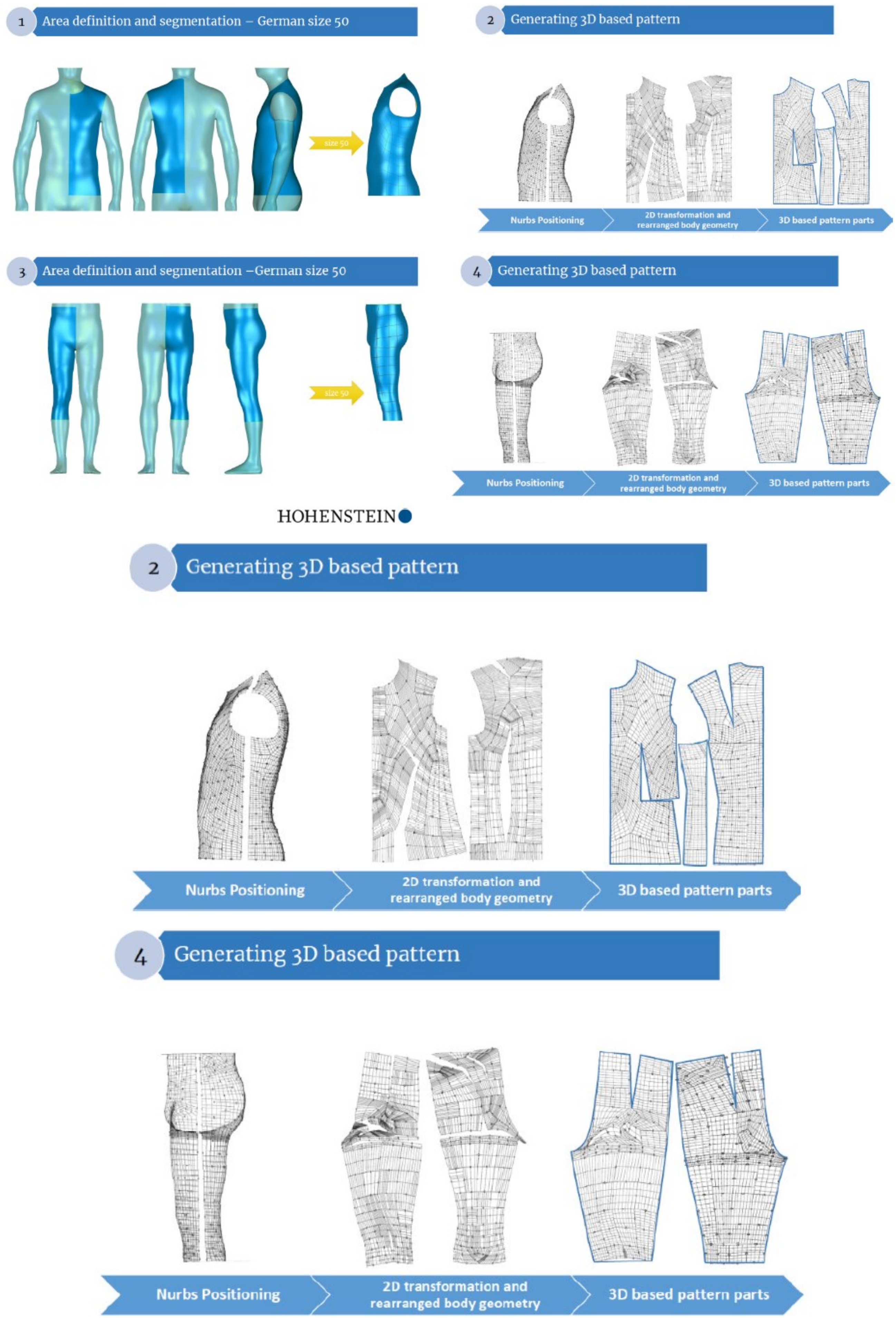


Fig. 8 Regional landmarks and split line for scanned body mesh flattening, adapted and used with permission.

A flattened mesh will not reveal nuanced and controlled shaping device placement. While the flattened pant image in Figure 8 hints a location for a crotch wedge, the mesh must be finessed to be considered production ready developable. Automating such practice has been challenging due to widely varying human morphology and a lack of theory for body-to-pattern geometric constraints. The bear skin method has limited use as a developable pattern with use cases currently restricted to products made from stretch materials. To be used for widespread product development, pattern theory regarding the principles of fit (set, line, ease, balance, and grain) would need to be evolved suited to this practice.

MOVE4D from IBV is a modular high-volume (e.g., ~16 m^3, 2 m x 3 m x 2.8 m) high-speed (up to 178 fps) and high-resolution (up to 1 mm) 4D scanner with integrated mesh processing software [20-22]. An output is shown in Figure 9. In addition to other deep learning models, MOVE4D software uses a shape and pose model and a proprietary template fitting algorithm to fit a 99k-tri template mesh to the point clouds captured at each frame of the dynamic sequence in a similar fashion to SCAPE [23] or alike. The shape is modelled as a PCA of 15k registered 3D scans in A-Pose from international databases [24]. Pose is modelled as LBS with 23 joint positions (or 63 in the version with hands and fingers) initialized based on International Society of Biomechanics (ISB) recommendations [25-27] and then optimized based on information learnt from IBV's datasets, and with skin attachments learnt from IBV's datasets. The resulting watertight meshes within a sequence and among subjects are homologous, which means that the meshes have a common topology and therefore vertex-to-vertex correspondence. Due to IBV's processing and to the by-products of it, namely the skin attachments and the estimation of the joint positions, MOVE4D can decompose each of the dynamic sequences into a combination of skinned animation (LBS) plus rigid animation (i.e., vertex displacement per frame). In this decomposition, the rigid animation expresses the residual soft-tissue deformation not expressed by the LBS modelling, i.e., the difference between the actual body surface captured at each frame and the A-pose avatar reposed using LBS to the estimated pose of each frame. This decomposition makes it possible to pack the avatar in the sequence into typical exchange formats such as FBX, glTF or USD and to be compatible with both apparel CAD (e.g. CLO3D or Optitex), to general purpose 3D modelling software (e.g. Blender or Maya) and to metaverse platforms (e.g. Unreal Engine, Unity or Nvidia Omniverse). Moreover, using A-Pose as rest pose and a convention of joint axes similar to the ISB, facilitates the reposing of the avatar using Euler angles.

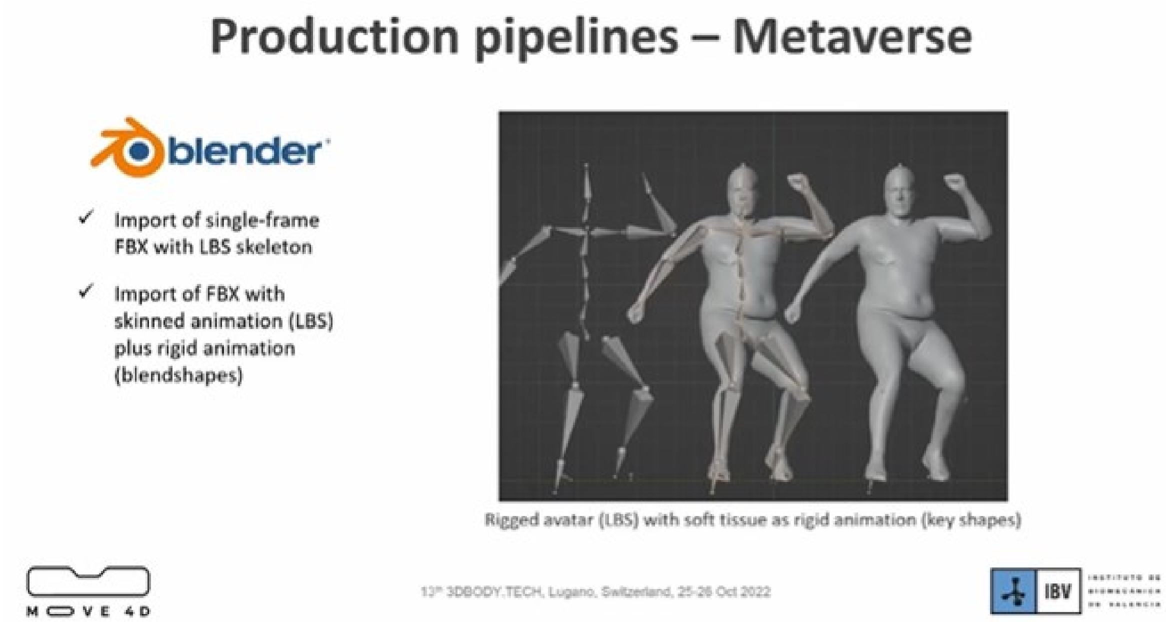


Fig. 9 Output from Move 4D from [22], adapted with permission.

Presently, skin modeling is accomplished by a three-part approach. The first approach is mesh surfacing modeling beyond a scan to create added textures such as adult acne, scars, moles, and etc. The use of mesh surfacing modeling is also dependent on the render engine used for the quality of realism required. The second approach is mesh morphing. A human form without undergarments will have a different exterior mesh shape than a human scan with undergarments. For example, the breast morph or testicular morphs will change depending on the undergarment worn. It is essential to understand the product that has been worn while the humanoid has been scanned. The face will also require reshaping in order for a digital twin to come to life. The third approach is UV map images using a multitude of programs. Depending on the program and approach taken to make skin covers, they may be dependent on the render engine utilized in some cases. For example, Arnold, the user may have more considerations to account for and want the highest definition possible, whereas a typical v-ray may also require a good understanding of lighting tools and sets but delivers less realism. The GPU/CPU relationship is also important to the ray tracing ability.

To gain texture, the industry can use various tools to gain an equivalent to 10k quality. Ultimately the higher fidelity rendering will come down to the lighting, render engines, and layers of UV maps such as bump, normal, displacement, and etc.

Note that skinning or weighting the rig to mesh is also a component; skinning weight is a larger subject that is connected to rigging and will not be covered in this paper.

9 Conclusions

The resulting meshes from MOVE4D dynamic captures constitute a departing point or ground truth for further research into the modeling of the “residual” soft-tissue deformation that cannot be expressed by LBS or other state-of-the-art skinning models. The ability to model to “residual” soft-tissue deformation is a limitation of today’s state of the art skinning models.

The long-term goal of presenting a constant standard that can be used in all programs and helps the designer with style line placement or landmarks associated with the style of the garment design is desired. This can be especially helpful when designing health wearables in apparel and accessories. Understanding the mesh as “truly” a skin and not a hard shell, will improve the modeling, rendering and animation of the garment and body interaction. The investigation of skin understanding from other disciplines (such as medical) may assist in the overall modeling of the skin alignment to the rig of the body scan (humanoid).

Current topology uses some of the BEST & MFL lines naturally (e.g., bending of the legs) for either rendering, or texturing that required for specific parts of the form while also considering the animation features. Expanding on the process presented in the landmarking paper [5], and utilizing the same reasoning, suggested that combining the suggested joint rigging from that paper along with the BEST/MFL and Langer’s lines (Figure 6 and Figure 7) are recommended, as it will impact the skin weighting and ultimately the animation considerations for 3D rotational movements in animation.

Authors Contributions

R. Rannow: investigation, writing – original draft preparation; A Ballester: investigation, resources, methodology, writing – original draft preparation; C McDonald: investigation, writing – original draft preparation; K Schildmeyer : investigation, methodology, writing – original draft preparation; E. Scott: methodology, writing – review and editing; S Gill: writing – review and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest other than A. Ballester works at IBV that produces the Move4D system.

References

1. Skin, Cleveland Clinic, https://my.clevelandclinic.org/health/articles/10978-skin (accessed 2023 March).
2. ISO/DIS 20947-3, Performance evaluation protocol for digital fitting systems – Part 3: Digital fitting performance. https://www.iso.org/obp/ui/#iso:std:77732:en.

3. Paul, S. Biodynamic Excisional Skin Tension (BEST) Lines, Revisiting Langer's Lines, Skin Biomechanics, Current Concepts in Cutaneous Surgery and the (lack of) Science behind Skin Lines used in Surgical Excisions. *Journal of Dermatological Research* March **2017**, *2*, 77-87. DOI: 10.17554/j.issn.2413-8223.2017.02.19 (accessed 2022-11-19).
4. Lemperle, G. Prevention of hyper-and hypotrophic scars through surgical incisions in the direction of the "main folding lines" of the skin. *Plastic and Aesthetic Research* **2020**, *7*, 40. DOI: 10.20517/2347-9264.2020.14.
5. Scott, E.; Schildmeyer, K.; Ruderman, G.; Ashdown, S.; McDonald, C.; Gill, S. Proposed Landmarking for Improved Digital Product Creation. *Communications in Development and Assembling of Textile Products* **2023**, *4*, 70-87. DOI: 10.25367/cdatp.2023.4.p70-87.
6. Kalra, A.; Lowe, A.; Al-Jumaily, A. M. Mechanical Behaviour of Skin: A Review. *Journal of Material Science and Engineering* **2016**, *5*, 1000254. DOI: 10.4172/2169-0022.1000254.
7. ISO 18825-2:2016, Clothing – Digital fittings – Part 2 Vocabulary and terminology used for attributes of the virtual body. https://www.iso.org/standard/63494.html (accessed 2022-12-27).
8. ISO 19774-1:2019, Information technology – Computer graphics, image processing and environmental data representation – Part1: Humanoid animation (HAnim) architecture, https://www.iso.org/standard/64788.html (accessed 2022-12-27).
9. Gill, S.; Scott, E.; McDonald, C.; Klepser, A.; Dabolina, I. Landmarking for Product Development. *IEEESA Industry Connections and Standards Group for 3D Body Processing Website*, PDF STDVA25126 978-1-5044-8226-4, https://standards.ieee.org/industry-connections/3d/bodyprocessing/ (accessed 2022-12-27).
10. Glascoe, W.; Schildmeyer, K.; Scott, E.; Gill, S.; Ballester, A.; McDonald, C. Relationships between Rigs and Humanoid and Coveroid Landmarks. *Proc. of 3DBODY.TECH 2022 – 13th Int. Conf. and Exh. on 3D Body Scanning and Processing Technologies*, Lugano, Switzerland, 25-26 Oct. 2022, #30, https://3dbody.tech/cap/papers2022.html.
11. SMPL, 2020 Max-Planck-Gesellschaft, https://smpl.is.tue.mpg.de/ (accessed 2022 November).
12. Xu, H.; Bazavan, E. G.; Zanfir, A.; Freeman, W. T.; Sukthankar, R.; Sminchisescu, C. Ghum & ghuml: Generative 3d human shape and articulated pose models. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, 2020, pp. 6184-6193.
13. Casas, D.; Otaduy, M. A. Learning nonlinear soft-tissue dynamics for interactive avatars. *Proceedings of the ACM on Computer Graphics and Interactive Techniques* **2018**, *1*, 1-15. DOI: 10.1145/3203187.
14. DYNA, Max Planck Institute for Intelligent Systems, http://dyna.is.tue.mpg.de/ (accessed 2022 November).
15. Villegas, R., Ceylan, D., Hertzmann, A., Yang, J., & Saito, J. Contact-Aware Retargeting of Skinned Motion. In *Proceedings of the IEEE/CVF International Conference on Computer Vision* 2021, pp. 9720-9729. https://arxiv.org/abs/2109.07431.
16. Pai, D. K.; Rothwell, A.; Wyder-Hodge, P.; Wick, A.; Fan, Y.; Larionov, E.; Harrison, D.; Raj Neog, D.; Shing, C. The human touch: Measuring contact with real human soft tissues. *ACM Transactions on Graphics (TOG)* **2018**, *37*(4), 1-12. DOI: 10.1145/3197517.3201296.
17. Casas, D., & Otaduy, M. A. (2021). U.S. Patent Application No. 17/076,660. Patent on Modeling of non-linear soft-tissue dynamics for interactive avatars. https://patents.google.com/patent/WO2019207176A1/en
18. Pai, D. Vital Mechanics, https://www.vitalmechanics.com/.
19. Paul, S. Biodynamic excisional skin tension lines for surgical excisions: untangling the science. *Ann. R. Coll. Surg. Engl.* **2018**, *100*(4), 330-337. DOI: 10.1308/rcsann.2018.0038.
20. Parrilla, E.;Ballester, A.; Parra, F.; Ruescas, A. V.; Uriel, J.; Garrido, D.; Alemany, S. MOVE 4D: Accurate High-Speed 3D Body Models in Motion. In *Proc. of 3DBODY.TECH 2019 – 10th Int. Conf. and Exh. on 3D Body Scanning and Processing Technologies*, Lugano, Switzerland, 22-23 Oct. 2019, pp. 30-32. DOI: 10.15221/19.030.
21. Ballester, A.; Parrilla, E.; Ruescas, A. V.; Uriel, J.; Alemany, S. To MOVE4D, or not to move, that is the question. *Proc. of 3DBODY.TECH 2021 – 12th Int. Conf. and Exh. on 3D Body Scanning and Processing Technologies*, Lugano, Switzerland, 19-20 Oct. 2021, #48. https://vimeo.com/633184432/fab288ca4c.
22. Manas Ballester, B. Yes, We Scan. *Proc. of 3DBODY.TECH 2022 – 13th Int. Conf. and Exh. on 3D Body Scanning and Processing Technologies*, Lugano, Switzerland, 25-26 Oct. 2022, #53. https://vimeo.com/755934295/8733132814.
23. Anguelov, D.; Srinivasan, P.; Koller, D.; Thrun, S.; Rodgers, J.; Davis, J. Scape: shape completion and animation of people. In *ACM SIGGRAPH 2005 Papers*, 2005, pp. 408-416. DOI: 10.1145/1186822.1073207.
24. Alemany, S.; Uriel, J.; Ballester, A.; Parrilla, E. Three-dimensional body shape modeling and posturography. In *DHM and Posturography*, 2019, pp. 441-457; Academic Press. DOI: 10.1016/B978-0-12-816713-7.00032-5.
25. Wu, G.; Cavanagh, P. R. ISB recommendations for standardization in the reporting of kinematic data. *Journal of Biomechanics* **1995**, *28*(10), 1257-1262. DOI: 10.1016/0021-9290(95)00017-C.
26. Wu, G.; Siegler, S.; Allard, P.; Kirtley, C.; Leardini, A.; Rosenbaum, D.; Whittle, M.; D'Lima, D. D.; Cristofolini, L.; Witte, H.; Schmid, O.; Stokes, I. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion – part I: ankle, hip, and spine. *Journal of Biomechanics* **2002**, *35*(4), 543-548. DOI: 10.1016/S0021-9290(01)00222-6.
27. Wu, G.; Van der Helm, F. C.; Veeger, H. D.; Makhsous, M.; Van Roy, P.; Anglin, C.; Nagels, J.; Karduna, A. R.; McQuade, K.; Wang, X. G.; Werner, F. W.; Buchholz, B. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion – Part II: shoulder, elbow, wrist, and hand. *Journal of Biomechanics* **2005**, *38*(5), 981-992. DOI: 10.1016/j.jbiomech.2004.05.042.