



3D skin length deformation of lower body during knee joint flexion for the practical application of functional sportswear



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ABSTRACT

With the advent of 3D technology in the design process, a tremendous amount of scanned data is available. However, it is difficult to trace the quantitative skin deformation of a designated location on the 3D body surface data during movement. Without identical landmarks or reflective markers, tracing the same reference points on the different body postures is not easy because of the complex shape change of the body. To find the least deformed location on the body, which is regarded as the optimal position of seams for the various lengths of functional compression pants, landmarks were directly marked on the skin of six subjects and scanned during knee joint flexion. Lines of non-extension (LoNE) and maximum stretch (LoMS) were searched for, both by tracing landmarks and newly drawn guidelines based on ratio division in various directions. Considering the waist as the anchoring position of the pants, holistic changes were quantified and visualized from the waistline in lengthwise and curvilinear deformation along the dermatomes of the lower body for various lengths of pants. Widthwise and unit area skin deformation data of the skin were also provided as guidelines for further use such as streamlined pants or design of other local wearing devices.

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1. Introduction

Observation of the extensible nature of the skin layer is essential in the ergonomic processes of various disciplines, not only for tissue engineering such as plastic surgery but also for advanced apparel technology. However, early references on the characteristics of the skin are typically derived from anatomists or surgeons, because the orientation of the skin layer must be considered to reduce scars from surgical incisions during surgery.

Among previous research, Karl Langer reported a series of directions of maximum skin tension called “Langer's lines” (Langer, 1978). Langer's lines are the natural orientation of the collagen fibrils, which are the base lines for skin surgery (Elsner et al., 2002). When surgical incision lines are made across Langer's lines, the surgical operation results in a robust scar formation that pulls the wound further open by high tension (Bethke, 2005; Wong et al., 2010). Langer's lines tend to be parallel; however, they form discrete groups that intersect each other. Later, Willhelmi et al. (1999) reported that Langer's lines change with body posture. He

suggested alternative guidelines for facial incisions called “Borges' relaxed skin tension lines (RSTLs),” and alternatives for body incisions called “Kraissl's wrinkle lines.” However, RSTLs also differ depending on the development of muscle, body posture, and body region. Furthermore, RSTLs are influenced by age, particularly in very young and old groups (Nizet et al., 2001; Hermanns-Lê et al., 2001).

Alternatively, Iberall (1970) observed directions of minimum skin extension during joint movement and illustrated lines of non-extension (LoNE) by connecting lines of minimum skin extension. He suggested the grid structure of LoNE for the space suit that was later further developed and digitalized by Bethke (2005). Bethke utilized a motion analyzer to trace the movement of sensors on the leg. Recently, Wessendorf and Newman (2012) further developed LoNE by adding the capability to track the direction of LoNE, minimum extension, and minimum compression during a squatting motion. However, due to the difficulty of tracking the reflective sensors, their strain field analysis did not include the highly extensible region of the posterior thigh near the hip.

Using 3D scanned data, Seo et al. (2013) estimated dynamic skin tension lines (DSTL) on part of the leg. They locally analyzed skin deformation and numerically computed the maximum tension directions by tracking the points drawn on the skin. Previous

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studies with DSTL demonstrated the nature of skin extension theoretically. However, they are not practical enough to adopt in the development of functional compression pants, due to a lack of visualization. To the best of our knowledge, 3D visualization of the skin strain field has been limited to the human ankle joint (Marreiros, 2010) or the inner part of the leg (Lee et al., 2013). In addition, DSTL have not included grooved areas of joints, such as under the hip.

From the viewpoint of apparel technology, 3D skin deformation of the whole body or lower body has been studied recently (Kim et al., 2012a, 2012b; Lee et al., 2013; Jeong and Lee, 2012; Watkins, 2011). Choi and Ashdown (2011) provided a careful procedure for 3D measurement of the human body for clothing construction, verified the accuracy of 3D measurements, and analyzed the change of body surface length and lower body circumference in standing and active postures. Their observation was limited to vertical and horizontal surface measurements, which are used for traditional clothing construction. However, in the construction of functional sportswear a streamlined design is currently preferred, and design lines may be curved. Quantification of deformation along the various curvature directions on the skin surface would be helpful for functional design lines and their fabrication using seams.

In fact, covering a large skin surface of heterogeneous extension with continuous textile materials without any stress is almost impossible. The deformation of a textile fabric may involve a non-uniform strain distribution in a complex deformation surface (Shanahan et al., 1978; Bondar et al., 1999). The heterogeneous and anisotropic nature of the skin is far more complex, due to localized wrinkles around joints as well as its intrinsic extensible properties. To overcome the different extensible properties between textile materials and skin, functional garment patterns are usually separated into panels. Panels of different strain are joined with stitches called “seams”.

One of the key variables affecting the performance and comfort of compression suits is the location and quality of the seams that join and assemble the pattern panels together. Although new technologies, such as welding and bonding, are available for seams in addition to conventional stitches (Choi et al., 2014), the unfavorable properties of seams such as weight, bulkiness, and impermeability may trigger disparate contact sensations on the skin during movement. Therefore, the location, flexibility, and elasticity of the seams should be carefully adjusted to avoid interference with the nature of the human body, including the stretch direction of the skin. With this purpose, several researchers have investigated ergonomic panel sectioning to identify seam locations.

For example, Jeong and Hong (2008) divided the textile materials based on the shape of muscles, with each panel allocated to a different percent of pattern reduction rate, resulting in high-performance cycle wear. Jeong and Lee (2012) further analyzed the 2D pattern considering 3D human body deformation. Wang and Tang (2010) addressed the problem of generating planar patterns from 3D body surface and computed strain generated by sewing the pieces of various panels and wrapping them onto the body. They proposed an algorithm to calculate the distortion and optimized the division of 2D patterns for compression garment.

Kim and Hong (2012) and Choi and Hong (2011) noted dermatomes as locations of seams. Dermatome is an area of the skin supplied by nerves from a single spinal root. Kim and Hong (2012) investigated the extension properties along the dermatomes of the lower body of a subject, and they found an interesting location of a LoNE near dermatome L4, among several dermatomes. The LoNE near L4 was used as a seam line in their work, and wearers positively evaluated the compression suits that adopted the LoNE near L4 as a seam. Further investigations of extensible properties along

the dermatomes with several subjects are necessary. If seams are inevitable in the fabrication of functional sportswear, the question arises whether a seam located at the boundary of a spinal nerve bundle would be in a better position to avoid an unpleasant contact sensation because of its location in between nerve bundles. Knowledge of the extension properties along the dermatome is also required. If a seam did not interfere with the extensible direction of skin, then the wear sensation would be better.

Practical observation of LoNE has not been performed extensively. Because LoNE for pants vary when the area of interest contains wrinkles and joints under the hip and knee, detailed guide lines are necessary. To date, the rationale for an optimal pattern of panel separation by seams in various directions has not been fully provided. This should be based on the skin deformation analysis of the lower body covering different lengths from waist to ankle, depending on the length of the pants. Recognizing that the extensibility of the skin is localized along the leg, skin deformation mapping should be separately provided or visualized depending on length of pants. The requirement for visualization of the 3D data

Table 1

Body dimensions of subjects scanned in this study. Unit: cm.

Measurement	Subject						Mean	S.D
	Standard				Overweight			
	A	B	C	D	E	F		
Stature	171.0	174.0	174.0	171.0	170.0	173.0	172.17	1.72
Weight (kg)	65.0	64.0	70.0	67.0	80.0	81.0	71.17	7.52
BMI index	22.2	21.1	23.1	22.9	27.7	27.1	24.02	2.72
Waist height	104.4	105.6	103.8	103.0	101.2	105.5	103.92	1.66
Waist height (Omphalion)	99.4	100.0	98.9	98.0	95.4	100.0	98.62	1.75
Crotch height	78.5	74.0	72.7	73.5	70.5	74.0	73.87	2.62
Knee height	43.0	47.0	45.6	46.0	42.5	45.0	44.85	1.76
Bust circumference	96.4	97.0	102.3	100.7	107.7	109.0	102.18	5.28
Waist circumference	76.1	76.2	80.0	75.5	95.4	94.5	82.95	9.43
Waist circumference (Omphalion)	77.5	79.1	82.6	79.5	96.9	97.2	85.47	9.12
Hip circumference	90.6	93.1	93.4	94.1	103.3	103.0	96.25	5.47
Mid-thigh circumference	50.2	49.0	55.8	52.6	62.5	57.4	54.58	5.03
Knee circumference	36.5	36.1	35.5	35.2	39.4	39.7	37.07	1.98
Ankle circumference	24.7	23.2	22.7	23.2	25.6	24.5	23.98	1.12
Crotch length (Omphalion)	63.8	68.5	68.1	70.3	69.5	72.5	68.78	2.90
Front leg centerline surface length (Waist to ankle)	97.9	97.4	94.7	92.1	97.3	99.6	96.50	2.67
Back leg centerline surface length (Waist to ankle)	99.5	98.7	94.6	90.1	96.9	99.7	96.58	3.71
Outside leg surface length (Waist to ankle)	97.9	96.7	93.8	90.2	96.0	99.8	95.73	3.36
Inside leg surface length (Tight to ankle)	62.0	63.1	62.1	56.3	59.1	60.9	60.58	2.50
Waist breadth (Natural indentation)	26.5	28.9	28.7	28.4	29.8	35.1	29.57	2.92
Waist breadth (Omphalion)	27.0	29.2	29.6	29.5	31.2	35.8	30.38	2.97
Hip width	32.0	33.1	32.9	32.5	33.5	32.5	32.75	0.53
Waist depth (Natural indentation)	19.8	21.1	21.2	23.4	24.2	27.9	22.93	2.92
Waist depth (Omphalion)	18.5	22.0	21.4	24.0	25.6	28.1	23.27	3.38
Hip depth	22.4	24.8	24.4	25.6	27.2	31.6	26.00	3.16

BMI: Underweight < 18.5; Normal range 18.5–25.0; Overweight 25.0 ~ 30.0; Obese > 30.0.

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