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Three-Dimensional Body Scan Data Analysis

Body Size and Shape Dependence of Ease Values for Pants' Fit

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Three-dimensional body scanning technology was used to analyze fit of women's pants and to measure garment ease at various locations. Special test pants constructed with adjustable Velcro sections were used to provide custom fit for each study participant. Twenty-four subjects, ages 35 to 55, represented three body shape groups (straight, medium, curvy) determined by the hip-to-waist circumferences ratio, and four size groups covering Misses size range 4 to 16. Scans of a subject wearing minimal clothing and of the same subject wearing the test pant, adjusted by the researchers for best fit in a standing position, were compared. The differences between the pant and body scans (ease) were determined for circumference, slice area, surface area, and volume measurements at various locations and analyzed for size and shape dependence. Decrease in percent ease differences with increasing size was observed for several variables; no clear dependence on shape was found. Size dependences were used to propose a way of pattern grading with grade intervals variable by size and body location.

Keywords: *3D body scan; apparel fit; garment ease; sizing; body shape*

The development of three-dimensional (3D) scanning technology in the past decade has attracted researchers in various spheres of the sciences and arts. Scanners use light to illuminate a scanned object, a series of cameras to capture the light reflected by the object, and a computer system to generate a 3D digital image of the object's surface. Scanning technology not only provides a realistic 3D visualization of objects but also allows unlimited retrieval of precise linear, two-, and three-dimensional measurements of objects' surfaces. Apparel scholars are challenged to explore the possible applications of scanning technology to develop new sizing systems, pattern-drafting methods, grading systems, 3D draping, virtual clothing interaction, etc.

Body scanning is less expensive, faster, and incomparably more detailed than traditional anthropometry; it has already been used for 3D anthropometric surveys, such as the Civilian American and European Surface Anthropometry Resource (CAESAR) survey (Air Force Research Laboratory, 2002), the United Kingdom National Sizing Survey (http://www.sizeUK.org.), the U.S. National Size Survey, and SizeUSA (http://www.sizeusa.com/). The collected scans are superior to

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traditional anthropometric data as measurements geared toward different applications can be done long after the scan is taken.

In the apparel industry, the ultimate goal is to have body scanners help customers acquire the most affordable, best-fitted clothing in the shortest amount of time. Researchers are using 3D scan data to develop various methods of creating a two-dimensional (2D) pattern for a well-fitted garment (Kang & Kim, 2000; Optitex, n.d.; Textile Clothing Technology Corporation, n.d.; Voellinger, 1998; Xu, Huang, Yu, & Chen, 2002) and to improve sizing systems (Ashdown, Loker, Schoenfelder, & Lyman-Clarke, 2004). Three-dimensional body scan data can be transferred to Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) tools, making the connection between the database and the design/manufacturing process very direct. Scanners are being used for custom-fit garment production by companies such as Brooks Brothers (n.d.), Saint Laurie (http://www.saintlaurie.com), and C&A (n.d.), and for customized pattern generation for home sewing by companies such as Unique Patterns (http://www.uniquepatterns.com). Scanners are being used for size selection by the U.S. Army (Morton, 1999) and by the Canadian Armed Forces (Department of National Defence and Canadian Forces, 2002), and for customers (e.g., http://www.intellifit.com/Intellifit/Home.aspx). The body scanning process is considered promising for the development of Internet-based "virtual try-on," whereby the customer can use his or her body scan to try on clothing digitally and to judge its fit and style remotely.

Many of these attempts to provide the best-fitted garment for a specific person involve a comparison between body and garment measurements: Either (a) the measurements of a garment are generated using the customer's body measurements, as in the case of custom-fitted garments, or (b) the measurements of an existing garment are compared to the customer's body measurements, as in the cases of fit analysis for virtual try-on, size selection, and development of effective standard sizing systems. The first case is somewhat easier to solve as traditional methods of construction can be applied to create a customized, well-fitted garment. The second case involves dealing with the complications of matching the measurements of a specific person to the measurements of a garment's sizing system, or finding the correct size. In both cases, the differences between body and garment measurements must be evaluated from the standpoint of good fit. Consequently, a reliable method of describing, defining, and predicting clothing fit is needed to use body scans for automated pattern development or for designing effective sizing systems for the population.

This research project is designed to investigate the relationship between what is described as good fit and the differences measured between a garment and a body. We secured good fit for a specific garment on a specific body, measured the garment-body differences at various body locations, and looked for a mathematical expression that would relate the measured garment-body difference with goodness of fit. Further, we assumed that the connection between fit and garment-body difference will depend on size and shape of the particular body and attempted to find this dependence. The basic assumption in our investigation was that body descriptors, such as size and shape, are correlated to the difference between the body and the shell wrapped around the body that a well-fitted garment represents, and thus to fit. Uncovering a mathematical representation of goodness of fit and linking it to size and shape holds the potential for improvement of sizing systems for ready-to-wear (RTW) as well as of customized apparel in terms of garment fit.

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Background and Justification

To fit the variety of shapes and sizes of the bodies in a population using standard body sizing systems, it is necessary to identify and define the size/shape groups based on a combination of key body measurements. The precision of a body sizing system in accommodating the population will increase as the number of key body measurements is increased. Decreasing the difference between two adjacent groups along a key dimension (intervals of the *body size table*) will also result in more sizes and therefore in an increased rate of accommodation (Koblyakova, 1974). However, a large number of sizes in a system can present manufacturers with issues (e.g., warehouse, distribution, and stocking excesses) related to the economy of producing garments for each size group (Brown & Rice, 1998; Koblyakova, 1974; Winks, 1997) as well as confusing customers in their choice of size.

Because there is no natural grouping of the population along body measurements, body shapes (as combinations of body measurements) continuously transform into one another making body shape categorization extremely difficult. Body size groups are formed by artificially partitioning the population's range of measurements. To optimize the number of size and shape groups in a body sizing system, the intervals between the different sizes have to be determined with respect to the relation of the bodies to the wrapped shell, that is the clothes (Koblyakova, 1974; Paal, 1997; Salusso Deonier, 1983). A sizing system that keeps this relation within an acceptable tolerance for all of the target market will provide good fit. However, determining the intervals of the set of body sizes within a body sizing system does not automatically mean that the intervals of corresponding garment sizing system (*grading rules*) have been determined. To "jump" from the body sizing system to the garment sizing system—that is, to create the grading rules that will make the set of garments fit the set of bodies—it is necessary to know that difference in measurement between each body and its garment that will secure good fit of the garment. The research presented in this article targeted exactly this link between body and garment sizing.

Because the current sizing standards—PS 42-70 (U.S. Department of Commerce, 1970) and its 1995 revision, D5585-95 (ASTM International, 1995)—are voluntary, manufacturers generally create their own sizing tables. For RTW clothing, most manufacturers base their sizing systems on an hourglass-shaped fit model (Connell et al., 2003) with specified key body measurements to develop a base size pattern. These patterns are scaled proportionally up and down to obtain different sizes of approximately the same shape, which limits the group of women who will be fitted well. Therefore, the existing sizing systems do not include significant portions of the population whose silhouette (body shape) differs from that of the fit model. Some manufacturers target populations with different proportions by employing fit models with body types that are different from the standard hourglass, but the range of variations in proportions are not extensive enough to accommodate the full variety of body shapes and types in the population. Customers who do not fit an existing size group exactly often are able to use mass-produced, RTW clothing because their bodies are somewhat accommodated by the extra fabric allowed over and above body measurements to ensure comfort, ease of movement, desired silhouette, and drape of the garment, or the wearing and style ease. However, the size labels assigned to clothing sizes do not

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provide specific information about the different proportions of garment measurements and are not consistent among manufacturers or retailers, often resulting in frustration while shopping.

Body Shape Categorizations

In the apparel industry, the significance of body shape is beginning to be widely recognized, as two people with identical key measurements will not fit in the same garment in the same way if their bodies are shaped differently. Constructed on the basis of a limited number of key measurements, a pattern often needs alteration to accommodate individuals whose shapes deviate from the shape for which the pattern was drafted originally. Thus, most alterations are shape dependent, and we postulate that fit is shape dependent too.

The most recent female body shape categorization systems for use in the apparel industry appear to be based on one of two major methods: (a) proportions of front and/or side silhouette widths—a method reported by Connell et al. (2003) or (b) proportions of body circumferences—a method developed by Simmons, Istook, and Devarajan (2004). The first method is more closely related to a visual method of shape determination in which only one body projection onto the view plane can be evaluated at a time. Often evaluating only one of the projections is misleading, as bodies with same front projection can have significantly different side projections and vice versa. Connell et al. (2003) achieve whole-body shape categorization by combining the results of the separate evaluation of nine body components—body build, body shape, hip shape, shoulder slope, front torso shape, buttocks shape, bust prominence, back curvature, and posture. Traditional garment pattern construction relies on circumferential and arc body measurements rather than on width (side-to-side in frontal view) and depth (front-to-back in side view) measurements. Therefore width/depth body shape categorization would be less related to patternmaking than would be circumference/arc shape categorization.

Combining width and depth projections is, to some extent, incorporated into the second method of shape evaluation, that is using ratios of body circumferences. This measure of shape allows for discrimination of two bodies that may have equal waist and hip widths, whereas the waist and hip depths are different. However, bodies with the same circumferential proportions may differ in width/depth proportion, or in some other shape-defining measurements, such as lengths, heights, or angles, rendering the circumferential proportion definition unable to differentiate shapes completely (Watkins, 1995). A more elaborate combination of circumferential/arc proportions along with width/depth proportions may be needed to define lateral body shape fully. In addition, body heights/lengths need to be combined with lateral body shape categories to achieve full body shape categorization.

Garment Fit and Ease

Traditionally, fit is described in terms of five components: *ease, line, grain, balance,* and *set* (Erwin, 1949). As each component interacts with all others, it is often hard to define one component without referencing another. Generally ease is divided in two types: (a) wearing ease—the amount of extra fabric allowed over and above body measurements to ensure comfort, mobility, and drape of the garment and (b) design ease—additional amounts of fabric added to achieve certain design effects by changing

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the line and shape of a garment. Because design ease is subjective, style dependent, and not essential to the basic understanding of fit, it will not be considered in this work.

Experience and common practice are the usual ways of determining the wearing ease values. Recommended amounts of wearing ease are given as a range of values in which the appropriate ease depends on the size and shape of the particular person, the experience of the patternmaker, the preference of the person for comfort ease, and the garment style. Although grade rules frequently specify larger increments between larger sizes, ease values are rarely specified for different sizes or shapes of the body.

Some researchers link the changes that the body undergoes while engaged in a physiological or physical activity to the calculation of ease values. Koblyakova (1980) provides minimum ease values for comfort of movement for upper-body garments based on the change of body circumferences during breathing. The ease is determined as the difference between body circumferences above bust, at bust, and at waist in a relaxed state and after taking a deep breath. The necessary minimum ease amounts are calculated as a percentage of the circumferences in relaxed state. Presenting the results as percentages hides the size dependence of the ease amounts—the higher the circumferences, the higher the ease amounts.

Kirk and Ibrahim (1966) propose that the stretch of the skin of the body during physical activities, such as sitting and bending, must be taken into account as basis for evaluation of fit performance of stretch fabrics. The results of the measurements of horizontal and vertical skin stretch at the buttocks, crotch, back, elbow, and knee during bending, stretching, and sitting are presented as a percentage of the corresponding body measurements, thus incorporating the size dependence of the amount of skin stretch.

In our study we adopted the idea of calculating the generalized ease amounts as a percentage of the corresponding body measurements: The difference between garment and body measurements was reported as a percentage of the corresponding body measurement. We call this *garment-body percent difference* or, for the specific garment we were investigating, *pant-body percent difference.* The sign of the measure indicates tightness (negative) or looseness (positive) of the garment at the location of measurement. Percent differences incorporate a positive size dependence into the final ease value: A specified percent difference would yield smaller ease amount for a smaller body measurement and larger ease value for larger body measurement. The same measures, expressed as proportion rather than percentage, are described by Yu (2004) as means of algebraic evaluation of fit of clothing. These authors call the measures *linear index, cross-sectional index* (for slice areas only), and *volume index.*

In the traditional methods of pattern construction, ease is added over the body measurements only at certain places. The refinement (*trueing*) of the pattern shapes between geometric key points leads to pattern shapes, which, when wrapped around the body, are assumed to provide the necessary ease at any given place. The 2D surface of a pattern when wrapped around a body forms a 3D surface of a garment around the 3D surface of the body. The gap between these two surfaces is unique, and its shape represents the global component of fit. Using 3D scanning technology we can visualize this gap by using two scans—the scan of a body and the scan of the body in the garment—and superimposing them. Mathematical description of this gap could lead to possible quantification of garment's fit. If the mathematical description of fit were linked unequivocally to the body 3D

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descriptors, such as size and shape, an automatic fit prediction could become possible.

The emergence of the 3D technology and body scanning has spawned efforts to digitally drape garments directly onto 3D body scans or models, that is, to wrap 2D patterns onto 3D models or to unwrap the 3D surface into 2D cloth. Speaking with mathematical rigor, such wrapping is impossible to achieve with absolute precision for the same reason it is impossible to depict faithfully the Earth's surface onto a flat geographic map. For garment draping, the achievable precision of the wrapping is sufficient with respect to seaming tolerances and fabric give. The fit of the wrapped/unwrapped garment, in contrast, is very important and needs to be calculated in such a way that the garment hangs at an appropriate distance from the body. Earlier versions of 3D from/to 2D either placed the cloth exactly onto the 3D model, not providing any garment ease, or let the garment sit at uniform distance away from the body (Xu et al., 2002). The commercially available pattern-making software *Optitex* (n.d.) provides the option of draping a created 2D pattern on a 3D model by setting all fabric parameters and the maximum tolerable pressure of the garment on the body (May-Plumlee, Eischen, & Bruner, 2004); ease is set by the patternmaker and tested with the software. For sloper creation, the *TC*^{2} (Textile Clothing Technology Corporation, n.d.) program uses segmented garment structure constructed to skim the surface of a body's 3D scan; again, ease is set by the designer. In view of these developments, it was our goal to explore the possibility of measuring the wearing ease values for well-fitted garments directly from 3D scans and provide an ease estimate that can be used for truly automatic patternmaking or for fit evaluation without digital draping.

Foundation of Present Study

The study reported in this article was designed based on the results of a large study that focused on development of a quantitative clothing fit evaluation methodology for RTW using body scan data (Ashdown, Loker, & Adelson, 2003), in which 160 women in Misses sizes 4 to 16, ages 35 to 55 years, were scanned in a body suit and in a pair of RTW pants, producing a body scan and a pant scan, respectively. The RTW pant was a straight, fitted pant with fly-front zipper closure, back waist darts, and a contoured 3 cm-wide waistband that formed a tilted pants waist sitting low in the front and high in the back. The pant size was selected to fit the participant well at the hip. The pant-body percent differences were extracted for the waist at the level of the top pant edge, the abdomen, and the hip. To link these percent differences to goodness of fit, three fit experts independently evaluated the fit of the pant for each participant and thus separated the subjects in three fit groups—*acceptable, marginal,* and *unacceptable*—with 54, 83, and 23 subjects in each group, respectively (Ashdown et al., 2004). Subjects were separated in three shape groups by the ratio of the hip and the natural waist circumferences (HWCR). These groups were designated *straight, medium,* and *curvy* (cutoffs at 1.26 and 1.33), with 52, 73, and 35 subjects, respectively. The main findings related to ease values from this previous study included the following: A. The overall averages of the circumferential pant-body percent differences at all locations were comparable for the sample of all 160 subjects and for the subsample of the 54 subjects with *acceptable* fit. However, the ranges of the circumferential pant-body percent differences were much narrower for the *acceptable* fit subjects, indicating that the percent difference

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measure is sensitive in the description of fit differences. B. Between any of the shape groups, the percent differences for waist and abdomen circumferences were significantly different ($p \leq .05$), whereas for the hip circumference they were not (because the pant was fitted to the hip), indicating that the pant fit different shape groups differently. C. From the 54 acceptable subjects, 11, 33, and 10 (21%, 45%, and 29%) subjects were from the *straight, medium,* and *curvy* shape groups, respectively, indicating that the pant generally fit the hourglass-like *medium*-shaped subjects better. D. The averages of the circumferential pant-body percent differences (ease) for the 54 *acceptable* subjects for waist, abdomen, and hip (1.8%, 2.5%, and 4.7%, respectively) were closest to the respective measures of the overall *medium* shape group of 73 subjects (1.8%, 2.3%, and 4.3%, respectively), whereas toward the waist, the pant's fit was tighter for the 52 *straight* subjects (–1.4%, 1.5%, and 5.0%, respectively) and looser for the 35 *curvy* subjects (7.3%, 4.4%, and 4.6%, respectively), which is also an indication that overall the pant fit the *medium* shape better and that there is a possibility that percent differences are shape dependent. E. The histogram of the size distribution was the narrowest for the *acceptable* subjects, widening and flattening for the *marginal* group, and even more so for the *unacceptable* group. This indicated that overall the pant had a tendency to accommodate the medium sizes better than the smaller or larger sizes. F. The hip percent differences within the *acceptable* group exhibited a tendency, although it was not significant, to decrease with increasing size, which indicated possible size dependence.

The narrow range of the circumferential pant-body percent differences for subjects with *acceptable* fit showed that these measures could be used for fit evaluation and discriminating good (or *acceptable*) fit (Ashdown et al., 2003). However, the described results of the RTW study provided numerical values for good fit mostly for the *medium* shape group. This fact prompted us to investigate further the possibility of shape and size dependence in the measures of fit. We designed a new study to explore the behavior of fit measures for all three HWCR shape groups and all Misses sizes and, possibly, to determine the values of fit measures that ensure good fit for the RTW Misses style pant used in the RTW study. To achieve good fit for every participant, we designed a special set of adjustable pants that were based on the pattern of the RTW. This permitted relatively rapid modification of the pants so that a study participant could be fitted well and scanned in a single fit session. The description of fit was based on the concept of wearing ease, which was expanded to include not only linear measures, such as circumferences or lengths, but also 2D measures, such as surface areas and slice areas, and 3D measures, such as volumes. This exploratory study had the following objectives: (a) to identify the wearing ease values at the waist, abdomen, and hip, which would provide good fit of a pant, (b) to investigate the ease values for size dependency (i.e., to look for evidence that the size of the body has an effect on the values of the pant-body percent differences), and (c) to investigate the ease values for shape dependency (i.e. to see whether the pant-body percent differences at each body location were different for different HWCR shape groups).

Methodology

Study Design

Measurements were made after capturing the surface of the body digitally using a

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Vitus/Smart 3D full-body scanner with laser light (Vitronic, n.d.). Manipulation of the raw scan data in preparation for measurements was made using commercially available software *PolyWorks v7.2*® (InnovMetric Software Inc., 2002). All measurements were made manually on the computer screen at body landmark locations determined for each individual participant.

To be able to achieve best fit of the pant during the fitting session, we constructed special adjustable pants that could change approximately 2 sizes up or 2 sizes down at each body location. Using these adjustable pants, we were able to fit the continuum of body shapes that each size group (as defined by hip measurement) exhibited. To cover the whole range of tested sizes, four pairs of adjustable pants were fabricated, each of which in its neutral position (i.e., not adjusted) was based on the pattern of the original RTW pants of Misses size 4, 8, 12, or 16. Once adjusted, the experimental pant did not correspond to any specific Misses size; thus we refer to the size of the adjustable pant as A, B, C, and D, corresponding respectively to sizes 4, 8, 12, and 16 in the neutral position. The experimental procedure included scanning of the participant in a close-fitting body suit and in the pants, adjusted for ideal fit as judged by the researcher.

Considering the exploratory nature of our work and the time-intensive data collection and measurement procedures employed, we recruited a small number of subjects: 24 subjects, 35 to 55 years old, who represented three body-shape groups (*straight, medium,* and *curvy*, with 8 participants in each group)—and four size groups (A, B, C, D, with 6 participants in each group). Body shape was defined for the lower body by the HWCR, which was determined from the body scan of each participant as follows: Hip circumference was measured in a horizontal plane at the level of the greatest protrusion of the right buttock from the frontal plane; the natural waist circumference was measured in a plane set as close as possible to the natural 3D waist curve of the participant, which was determined by the position of an elastic band set at the waist prior to scanning. Participants had HWCR ranging between 1.03 and 1.41. In the *straight, medium,* and *curvy* groups, HWCR averages were 1.17, 1.29, and 1.37, respectively. The variation in crotch depth (i.e., height difference between the waist level and the crotch level) was not included in the analysis even though it is important for body shape definition of the lower torso; we controlled for this variation by adjusting the pant vertically.

The size of a participant was determined by the size of the RTW pant that fit the participant best on the hip; consequently, a participant was placed in one of the size groups, A, B, C, or D. The hip circumferences for the 24 participants ranged from 870 mm to 1257 mm. Because shape groups ordered as *straight-medium-curvy* corresponded to increasing HWCR and size groups ordered as A-B-C-D corresponded to increasing hip circumference, for statistical purposes, size and shape could be considered an interval and an ordinal variable, respectively.

Test Garment: Adjustable Pants

The pattern of the RTW pant from the RTW study was also used as the basic pattern for the adjustable pant. The following changes were made to simplify the procedures necessary to custom fit the test pant: The nonfunctional shaped waistband of the original pattern incorporated into the front and back panels of the adjustable pant, introducing a front dart; the pant was shortened to knee length for easier handling (see Figure 1). Adjustability of the test pant was achieved by slicing the pattern of the pant

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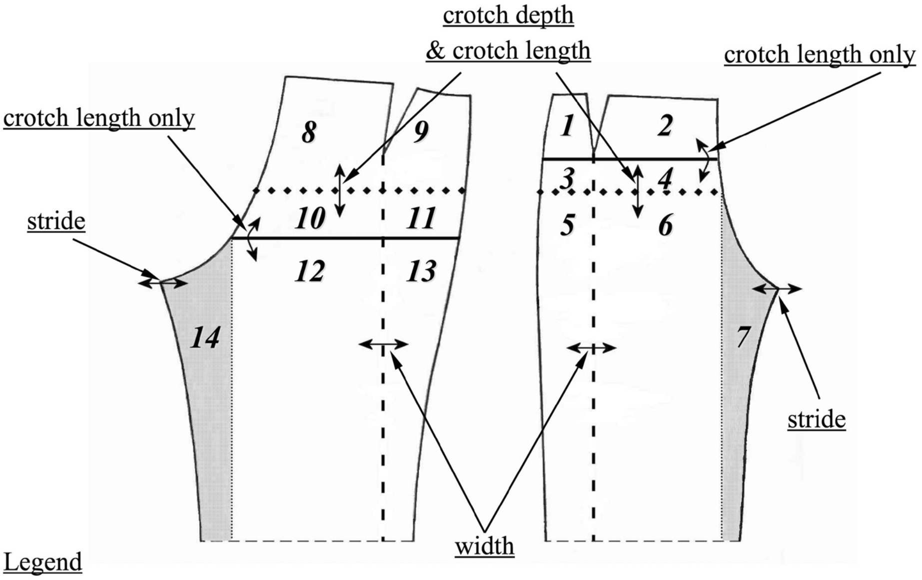
Figure 1
Pattern Sections (Numbered) and Adjustment Lines Used in the Test Pants



Legend
- dashed lines: overall width adjustments
- diamond lines: crotch depth and crotch length adjustments
- solid lines: crotch length adjustments only—pieces pivot from side seam
- shaded pieces: full pieces interchanged with different sized pieces to adjust stride

Note: Double-sided arrows show areas of adjustment: Pieces are moved in (tighter) or out (looser) from a center baseline. All sections move together (i.e., for a front width adjustment sections 1, 3, and 5 move as a unit in relation to sections 2, 4, and 6).

along all major adjustment lines for a pant as advised in the literature (Cauley & Maehren, 1989), producing pieces 1 to 7 for the front panel and 8 to 14 for the back panel (see Figure 1). Pieces were extended appropriately so that they could be spread apart or overlapped, thereby increasing or decreasing the size of the test pant. Adjustable pieces were secured using lightweight Velcro hook-and-loop materials, which formed a closure with thickness of only 0.96 mm and a very strong bond when subjected to shear forces, thus allowing for accurate matching along adjustment lines. A measuring grid (see Figures 2 and 3) was incorporated along each opening to allow for precise control of the adjustments. An accurate grid was generated on a computer, printed on iron-on paper sheets, and transferred onto the right side of each section of the pants. At each adjustment location, the total range of possible adjustment was 3 cm up and 3 cm down from the base size line in 5 mm increments (i.e., approximately 2 sizes up and 2 sizes down). The grid used for the adjustment of the crotch line allowed for up to 3 cm increase or 3 cm decrease in the length of the crotch line in 5 mm increments as measured along the center back and center front seams.

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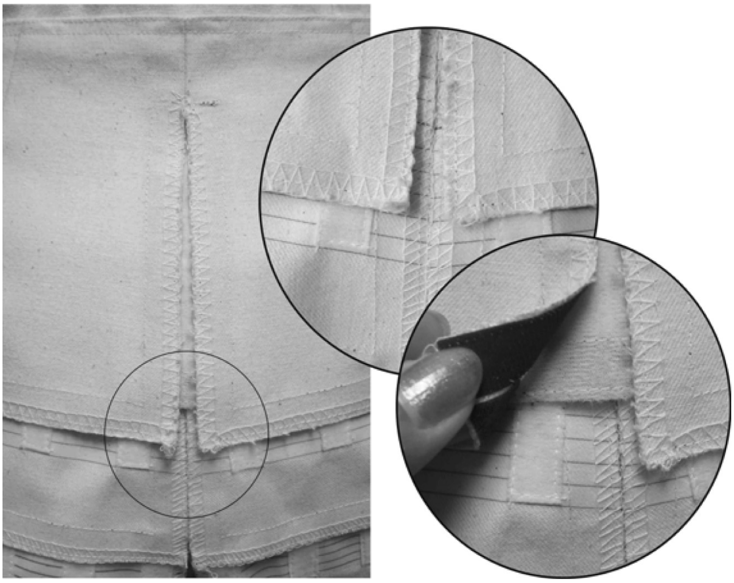
Figure 2

Use of a Free-Standing Velcro Patch to Secure the Center Back Seam. The Velcro Connects the Upper Left and Right Back Hip Pieces (Section 8, see Figure 1) as the Back Seam Is Trued After a Crotch Length/Depth Adjustment



The crotch depth was controlled with vertical adjustments made along the diamond line shown in Figure 1: The upper portion of the pant (pieces 1, 2, 3, 4, 8, 9) could be separated and moved an equal amount up or down all around the pant from the pant's lower portion (pieces 5, 6, 10, 11, 12, 13), thus achieving deeper or shorter waist-to-crotch depths. Pieces 1 and 3 were sewn along the side seam to piece 9; pieces 11 and 13 were sewn to piece 5. The shape of the side seam was not adjustable, but when it was necessary to change the curve, the side seam was pinned along piece 5. Trueing of the pattern along the crotch line was achieved by separating pieces 2, 4, and 8 along the crotch seam and attaching them to a separate section of Velcro loops (see Figure 2). Circumference adjustments were made along the dashed lines shown in Figure 1: Each of the piece pairs 1 and 2, 3 and 4, 5 and 6, 8 and 9, 10 and 11, and 12 and 13 could be adjusted separately, providing that the adjustment between two adjacent pairs is continuous. The width adjustment could be made at an angle to the grain direction of the original pattern, thus allowing for dart-type manipulation of the pattern. Adjustments along the crotch seam, also called crotch length, were made when the crotch depth was adjusted. Additional crotch length adjustments could be made separately for the front and back panels using wedge alterations along the solid lines in Figure 1: pivoting at the side seam, pieces 1 and 2 could rotate toward or away from pieces 3 and 4 in front (see Figure 3), and pieces 10 and 11 could rotate toward or away from pieces 12 and 13 in the back.

Because the original RTW pant had a very high back waist level, it was necessary to have the option of lowering the level of the

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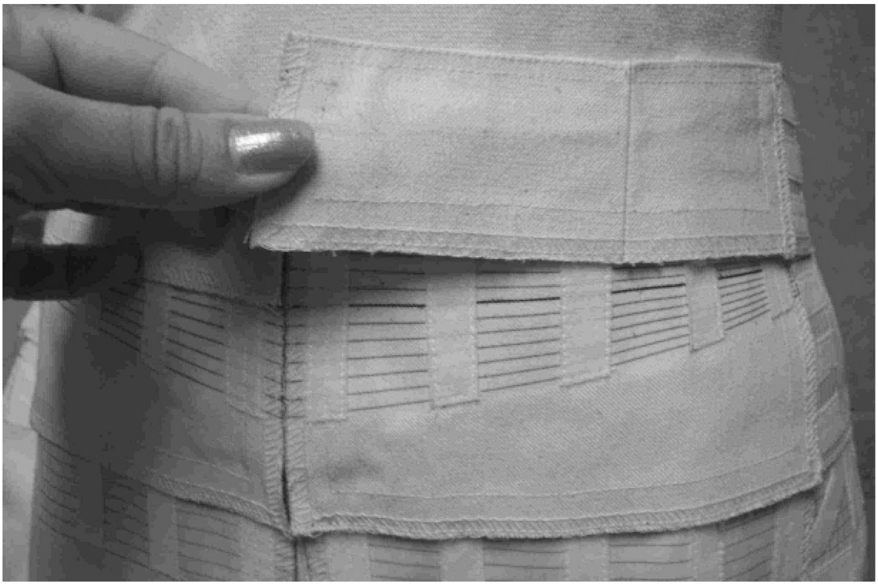
Figure 3
Example of Front Crotch Length Wedge Adjustment: Pivoting Sections 1 and 2 With Respect to Sections 3 and 4



back waist. That was achieved by means of a second interchangeable upper-center back panel (left and right pieces 8 joined) with a waist level of about 1.5 cm lower than the original pattern, where the exact value varied slightly with size because of trueing.

A specific alteration important to pant fit is pant stride. Referring to Figure 1, stride is the additive of the widths of the shaded pieces 7 and 14 at the level of the crotch point. This measurement is related to the front-to-back body depth of the lower torso. Stride was controlled to some extent by the general pant width adjustments. To control the stride of the pant separately from the crotch depth adjustment, we created a set of removable and interchangeable saddle-like pieces, each with a different stride width ranging from 10 cm less to 30 cm greater than the original pant in 5 mm increments (see Figure 4). The saddle-like pieces were created in the following way: From basic pieces 7 and 14, a number of pieces were derived for which the crotch point moved horizontally to increase or decrease the stride in 5 mm increments. Trueing at the crotch point was achieved through adjustments of the inseam lines and slight adjustments of the front crotch curve in piece 7 so that vertical movement of the crotch point associated with conventional trueing is prevented. Front and back pieces with appropriate crotch point positions were combined and sewn together to form various saddle crotch pieces. Saddle crotch pieces were attached with Velcro to the front pieces 6 in front and the back pieces 12 with no adjustments along the attachment lines. For each size pant (A, B, C, or D), there were a total of nine saddle crotch pieces, allowing for stride width adjustment of the pant without affecting the crotch depth. In the course of

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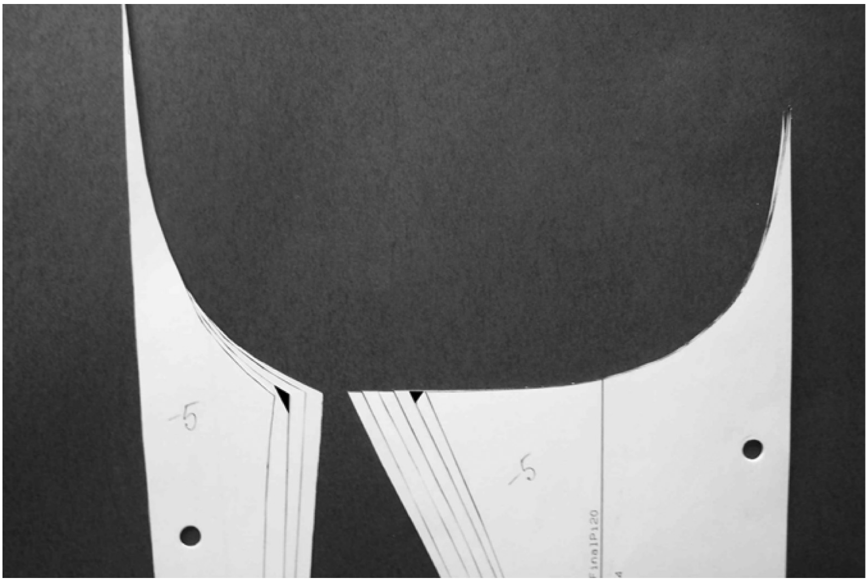
Figure 4
Nested Set of Patterns for Crotch Pieces With Different Strides Derived From Front and Back Crotch Pieces (Pieces 7 and 14 in Figure 1)



the experiments, all of these crotch pieces were used except for the two largest.

The adjustable pant was made from a fabric that was comparable to the fabric of the original RTW pant in weight, thickness, and stiffness (see Table 1). The multiple layers of fabric, Velcro materials, measuring grid material, and stitching at junction points of the adjustable pieces increased the thickness and the stiffness of the adjustable pant at some locations where the behavior of the layers was comparable to that of the waistband of the original RTW pant (see Table 1). However, because the adjustable pant required multiple junctions, overall, it was somewhat stiff and did not drape as the original pant did. Although the Velcro was able to withstand very well the pressure exerted by walking, it did tear away when subjects tried to sit.

A pilot test was conducted to experiment with the manipulation and fitting of the adjustable pant. The researcher fitted the pants multiple times to determine the best and most rapid sequence of making the necessary adjustments. Further, the pilot tests also included taking all necessary manual and scan measurements to develop a protocol for retrieving and handling the data.

Procedure

On arrival, the purpose and the procedure of the experiment were explained to the subjects, and they were asked to read and sign a form indicating consent to participate in the study and giving permission for the use of the collected data. An incentive fee of $20 was paid to each subject for about an hour of her time. To be scanned, the participant was asked to don a Lycra body suit over her ordinary underwear. The body height, weight, crotch length, and crotch height (that is the height of the crotch point from the floor) were taken

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Table 1
Weight[a], Thickness[a], and Stiffness (Bending Moment)[b] of the Fabrics Used in the Original Ready-to-Wear (RTW) Pant and the Adjustable Pant

	Weight g/m^2	Thickness mm	Bending moment[b] g*cm
Original RTW pant[c]			
Fabric (100% cotton, 3/1 twill)	277	0.50	0.30
Multiple layers at waistband		1.89	17.5
Adjustable pant[c]			
Fabric (100% cotton, 2/1 twill)	247	0.41	0.38
Multiple layers at pieces' junctions		1.95	17.8

a. Standards ASTM D3776-02 and ASTM D1777-02 were followed in the measurements of fabric's weight and thickness, respectively.

b. Bending test was performed with a Taber V-5 stiffness tester where 1 Taber stiffness unit = 1 g*cm.

c. The results are averaged for three test samples.

manually. An elastic band was placed around subject's natural waist prior to scanning to create a waist landmark in the scan. The size of the participant was determined by finding the Misses RTW original pant that fit her best at the hips. A scan of the subject only in the Lycra suit was taken to represent her body (body scan). Next, the adjustable pant was modified to fit the participant according to the judgment of the researcher and a scan was taken (pant scan). Each adjustment was recorded manually.

The set of adjustments were done according to the researcher's judgment about what constitutes a good fit following the standards for fitting the lower torso and legs described by Leichty, Pottberg, and Rasband (1992). The fitting of the adjustable pants began by making rough width adjustments around the area of the largest body girth of the participant while maintaining the side seam balance in the correct position. Next, the crotch depth was adjusted to position the waist level of the pant approximately in the correct place. Additional adjustments of the front/back waist level were made using the wedge adjustments of the front/back crotch length and/or using the alternate upper-center back waist panel (left and right pieces 8 joined) with the lower back waist level. Next, starting at the hip level and working up toward the waist, the width adjustments were refined. For participants with a very round abdomen, the abdomen was compressed slightly to create a smoother fit and a less curved silhouette at the waist. In these cases, the pant width at the hip in front was set loose enough to allow the pant to hang straight down from the abdomen, rather than follow the extreme curvature of the body. Keeping the pant balanced, the thigh width and stride width were adjusted to allow the pant to hang smoothly below the hip without bagginess below the buttocks and the abdomen. Because the side seam could not be adjusted, when it was necessary to flatten the shape of this seam, the fabric was pinned on the side.

The pants were fitted only for a standing position. However, subjects were encouraged to move, stretch, or change posture to prevent possible swelling and aches of the legs, light headedness, or fainting that might ensue from prolonged standing during the fitting (about 30 min). Such motion also allowed the pant to settle correctly over the body and to reveal if any further adjustments were necessary.

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Scan Measurements

Scans were prepared for measurement by filling in missing areas (holes) in the scan surface that would result in inaccurate values for linear and 2D measurements and prevent volume measurements. The crotch area requires the most reconstruction because it is missing completely from the scans, as the cameras cannot capture an image in this area. To restore the crotch area accurately, saddle-like shaped patches were placed to match the level of the crotch height that was taken manually during the fittings. After all holes were filled, 12 planes intersecting the body scans in various body landmark locations and 1 plane intersecting the pant scan through the top of the waistband were set for each participant to define measurement locations.

The following types of measurements were taken: Linear measurements included circumferences, lengths along the scan's surface, and depths and widths through the scan; 2D measurements included surface areas on the scan's surface and slice areas of the scan; 3D measurements included volumes of selected sections of the scan. Planes were placed at the natural body waist (i.e., closest to the elastic band placed on the body prior to scanning, pant waist (i.e., closest to the top of the pant at waist), abdomen (i.e., the level of greatest protrusion of the abdomen from the frontal plane), hip (i.e, the level of the greatest protrusion of the right buttock from the frontal plane), thigh (i.e., the level 7 cm below the crotch level), crotch (i.e., the level of manually measured crotch height), bulge (i.e., the level of the widest lower body width in the frontal view), the sagittal plane (i.e., a center plane separating the body into left and right sections). At each location the body and the pant scan were measured, the difference calculated and presented as a percent of the corresponding body measurements—what we termed pant-body percent differences. Where appropriate, both full and front/back measurements were taken. Front/back body portions were defined using a frontal plane placed at a side seam position defined as halfway through the right leg at the thigh level.

Descriptive statistics (mean, minimum, maximum, range, standard deviation) were calculated and compared for each variable. One-way analysis of variance (ANOVA) tests were carried out to test each variable for significant differences between the three shape groups and the four size groups. Post hoc comparisons using Bonferroni tests were used to determine which groups exhibited significant differences. Because the sample was small in size, possibly preventing establishing normality of the population from which the sample was drawn, the alternative of ANOVA—nonparametric Kruskal-Wallis tests—were also performed. The Kruskal-Wallis test does not require that data come from a normal population, but it still requires that variance of compared groups be equal, which was checked using the Levene test of equality of variance. Pearson correlation coefficient was used to estimate the strength of linear association of each variable with shape and size.

Results

Table 2 presents the results for the minimum, maximum, and average pant-body percent differences as well as the standard deviation of the circumferences at the waist, abdomen, hip, and thigh that were found in the study. These pant-body percent differences can be translated into wearing ease values that would provide good fit for the test pant. Results show that, moving from the waist down toward the thigh, the average pant-body percent differences at each body area increases in value. Table 2 also presents the minimum, maximum, and average pant-body percent differences and standard deviations for

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Table 2
Descriptive Statistics, Analysis of Variance (ANOVA) *F* Statistic, and Post Hoc Test (Bonferroni Procedure) Results for the Pant-Body Percentage Differences by Size and Shape Group for the 24 Study Participants

Pant-body percent Differences (%)	Minimum[a]	Maximum[a]	Averages	Standard deviation[a]	ANOVA and Size-Group Averages[b]					ANOVA and Shape Group Averages[c]			
					F (3, 20)	A	B	C	D	*F* (2, 21)	Straight	Medium	Curvy
Waist	–1.7	6.9	1.7	2.3	1.0	1.6	2.9	1.9	0.6	1.0	1.9	0.8	2.5
Abdomen[d]	–0.1	7.3	2.7	1.5	2.2	3.6	2.5	3.2	1.7	3.7*	2.4_a	2.0	3.8_a
Hip	2.7	6.9	4.8	1.2	2.8	5.9	4.5	4.7	4.1	0.6	5.0	4.4	5.1
Thigh	0.3	27.5	15.8	4.2	1.1	14.4	14.1	17.4	17.3	3.0	18.5	14.1	14.8
Slice areas													
Waist	–3.3	14.9	3.7	4.6	1.2	3.6	6.2	3.5	1.3	0.8	4.4	2.0	4.6
Abdomen[d]	0.2	13.7	5.5	2.9	3.3*	7.4_a	5.3	6.3	3.0_a	4.6*	4.8_a	4.1	7.7_a
Hip	5.8	14.1	9.6	2.2	3.6*	11.5_a	9.6	9.2	7.9_a	0.7	10.2	8.9	9.6
Thigh	17.2	57.0	29.1	9.1	0.9	26.9	25.2	32.0	32.4	2.5	34.4	25.2	27.7
Surface areas													
Waist-abdomen	–2.1	7.1	1.8	1.9	4.0*	3.4_a	1.2	2.3	0.4_a	4.3*	0.9_a	1.4	3.2_a
Abdomen-hip	1.0	8.5	4.1	1.8	6.6*	6.0_a	3.8	3.8	2.6_a	1.9	3.5	3.6	5.0
Hip-thigh	1.6	10.5	5.6	2.5	0.6	6.6	5.0	4.9	5.8	2.4	7.1	4.8	4.9
Volumes													
Waist-abdomen	–2.7	10.9	3.4	3.0	3.0	4.9	4.1	4.1	0.6	1.6	3.0	2.3	4.9
Abdomen-hip	4.1	14.2	8.2	2.5	12.5*	11.3_{abc}	7.9_a	7.9_b	5.7_c	1.2	7.8	7.5	9.3
Hip-thigh	9.8	25.7	16.0	4.2	0.5	17.7	14.6	15.7	15.8	5.1*	19.2_a	14.7	14.0_a

Note: In the same row, for a given ANOVA analysis, the means of two size or two shape groups carry the same subscript if their means differ significantly at $p \leq .05$ level in the Post Hoc tests (Bonferroni procedure).

a. $N = 24$.

b. $n = 6$ for each size group.

c. $n = 8$ for each shape group.

d. For the shaded variables, the Kruskal-Wallis test did not find significant differences between the means of the groups.

*$p \leq .05$.

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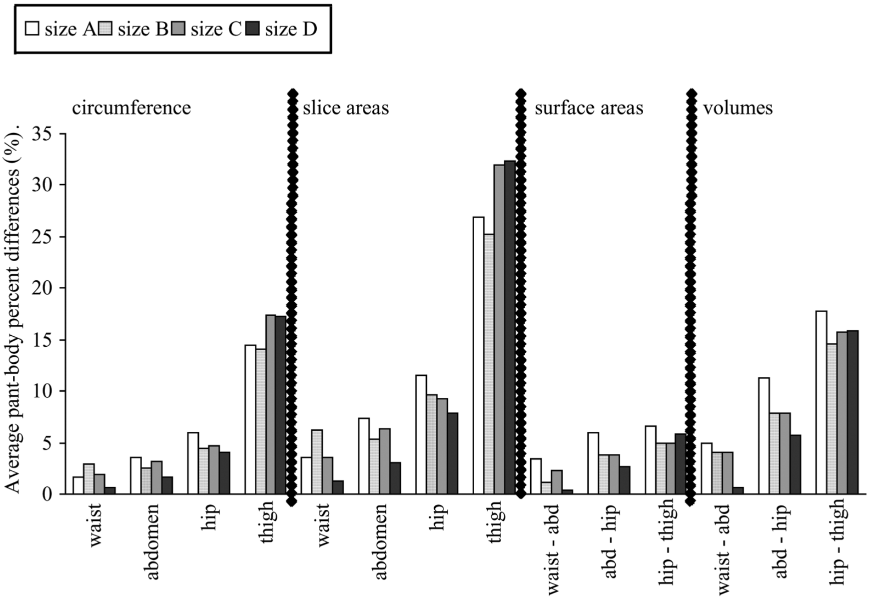
Figure 5
Average Pant-Body Percent Differences by Size Group (4 Groups, *n* = 6) for Circumferences and Slice Areas at Waist, Abdomen, Hip, and Thigh and for Surface Areas and Volumes for Waist-to-Abdomen, Abdomen-to-Hip, and Hip-to-Thigh Regions



the slice areas at the waist, abdomen, hip, and thigh, and for the surface area and volume for the waist-to-abdomen, abdomen-to-hip, and hip-to-thigh body sections, where the tendency of the average values to increase from the waist down is repeated.

The average pant-body percent differences for all variables and locations for each of the four size groups are shown in Table 2 and graphically on Figure 5. With few exceptions, the trend of the average pant-body percent differences to increase from the waist down is exhibited within each size group. Examination of the size dependence of the variables shows an overall tendency of the average percent differences at any body location to decrease with increasing size, suggesting a negative dependence of the average pant-body percent differences on size. As noted before, the expression of the pant-body differences as a percentage of the body measurement incorporates a positive dependence of the nominal values of the pant-body differences (i.e., wearing ease values) on size. This positive size dependence of the percentage measure itself counteracts the negative size dependence of the pant-body percent circumference differences and the exact values of the wearing ease will depend on the strength of this interaction.

Statistical examination of the size dependence of the pant-body percent differences using one-way ANOVA showed that there are significant differences ($p \leq .05$) between the size groups of the following variables (see *F* statistic results in Table 2): slice area of the abdomen and hip levels, surface area

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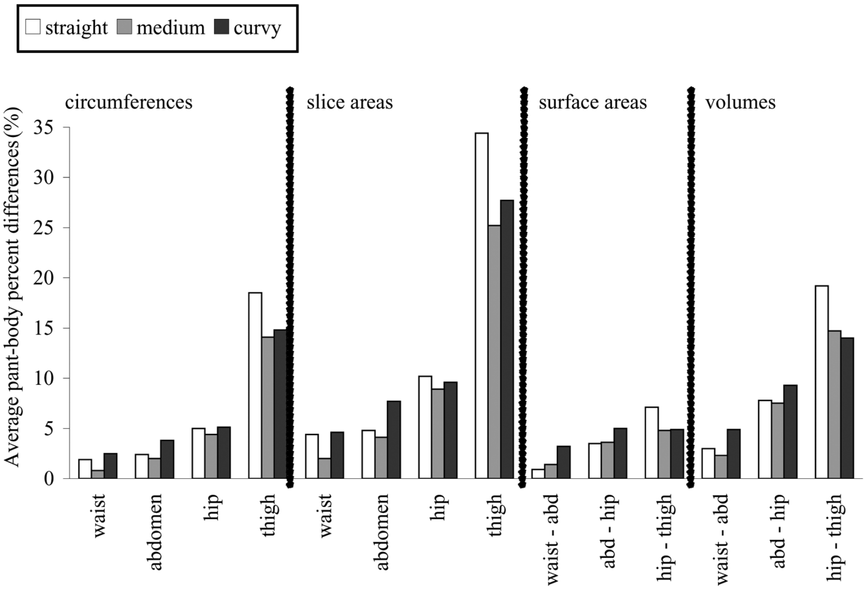
Figure 6
Average Pant-Body Percent Differences by Shape Group (3 groups, $n = 8$) for Circumferences and Slice Areas at Waist, Abdomen, Hip, and Thigh and for Surface Areas and Volumes for Waist-to-Abdomen, Abdomen-to-Hip, and Hip-to-Thigh Regions



of the waist-to-abdomen and abdomen-to-hip area, and abdomen-to-hip volume. Post hoc tests using Bonferroni procedure identified the significant differences between the following size groups noted in Table 2 with matching subscripts: A and D for the abdomen slice area, hip slice area, waist-to-abdomen surface area, abdomen-to-hip surface area, and abdomen-to-hip volume; A and B and size groups A and C for the abdomen-to-hip volume. The results of the nonparametric Kruskal-Wallis tests concur with the findings of the ANOVA.

The average pant-body percent differences for each of the three shape groups (*straight, medium,* and *curvy*) are presented in Table 2 and graphically on Figure 6. The average pant-body percent differences increase from the waist within each shape group. No clear shape dependence is observed except that the percent values for the *medium* group are the lowest of the three groups for all variables and locations except in three cases. One-way ANOVA and post hoc tests found significant differences between the averages of the pant-body percent differences for the following groups: *medium* and *curvy* shape groups for the abdomen circumference and the abdomen slice area (these were not confirmed by the nonparametric Kruskal-Wallis tests), *straight* and *curvy* shape groups for the waist-to-abdomen surface area and hip-to-thigh volume.

Correlation tests of the pant-body percent differences for all variables with size and HWCR were conducted. Results for the Pearson correlation coefficient r are presented in Table 3. Except for the percent

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Table 3
Pearson Correlation Coefficients (*r*) of Pant-Body Percent Difference of Different Variables at Different Locations With Hip-to-Waist Circumference Ratio (HWCR) and With Size

Pant-Body Percent Difference	Pearson Correlation Coefficient (*r*) of Pant-Body Percent Difference	
	HWCR	Size
Circumferences		
Waist	0.096	–0.196
Abdomen	0.370	–0.374
Hip	0.036	–0.476*
Thigh	–0.366	0.328
Slice areas		
Waist	0.023	–0.243
Abdomen	0.414*	–0.480*
Hip	–0.103	–0.572*
Thigh	–0.309	0.292
Surface areas		
Waist-to-abdomen	0.516*	–0.476*
Abdomen-to-hip	0.347	–0.652*
Hip-to-thigh	–0.366	–0.105
Volumes		
Waist-to-abdomen	0.259	–0.485*
Abdomen-to-hip	0.248	–0.758*
Hip-to-thigh	–0.529*	–0.129

Note: $N = 24$.
*$p \leq .05$.

differences of the circumference and slice area of the thigh, which correlate positively with size, the percent differences have negative correlations with size, which become stronger moving from the waist down towards the hip. The negative correlations for the percent differences of the surface area and the volume for the hip-to-thigh section are very small: –.105 and –.129, respectively.

No obvious relation between the average percent differences and HWCR is evident in Table 3. However, the correlation tests shown in Table 3 indicate that for the variables that are not related to the thigh measurements, there is either positive, none, or a very small negative correlation with the HWCR. Although the results are not conclusive, there appears to be a tendency for the percent differences of the variables not related to thigh to correlate negatively with size while correlating positively with HWCR.

Discussion

Wearing Ease Values

The first objective of this study was to identify the pant-body percent differences that will ensure good fit of a specific style RTW pant fitted to women of a wide range of body shapes and sizes. The developed adjustable pant allowed us to secure good fit for all 24 participants in the study. The circumferential pant-body percent differences at waist, abdomen, and hip (see Table 2) found to ensure good fit were compared with the corresponding data for the 54 participants in the RTW study (Ashdown et al., 2003), who were evaluated to have acceptable fit for the same RTW pant style. The comparison revealed (see Table 4) that the redefined ranges for the wearing ease were generally narrower, and the standard deviation was generally slightly less for the 24 study participants than for the 54 participants in the RTW study. The difference between the smallest and largest ease value decreased by 4% at the waist and 2.9% at the hip for the study participants, whereas the range increased slightly (by 1.5%) at the abdomen for the 24 study participants. The averages between the two groups were comparable: They differed by only 0.1% to 0.2%. Although these values do not appear to be very different, it is important to recognize that the 24 subjects equally represent the full range of sizes (i.e., groups A, B, C, and D) and all three shapes (*straight,*

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Table 4
Descriptive Statistics for the Pant-Body Percent Differences of Circumferences for the Subset of Subjects From the Ready-to-Wear Study Rated With Acceptable Fit (*n* = 54, Mostly *Medium* Shape) and the Current Study Subjects (*N* = 24, All Shape Groups)

Pant-Body Percent Differences of Circumferences (%)	Range: Minimum	Range: Maximum	Average	*SD*
Waist				
RTW study: acceptable only	–3.9	8.7	1.8	2.6
Current study	–1.7	6.9	1.7	2.3
Abdomen				
RTW study: acceptable only	0.3	6.2	2.5	1.3
Current study	–0.1	7.3	2.7	1.5
Hip				
RTW study: acceptable only	1.7	8.8	4.7	1.7
Current study	2.7	6.9	4.8	1.2

medium, and *curvy*), whereas the 54 RTW subjects rated with *acceptable* pant fit were mostly from size groups A and B (80%) and primarily from the *medium* shape group (62%). Therefore, the results of our study are not a simple replication of those of the RTW study: We enhanced the applicability of the results by encompassing the full range of body shapes and sizes. In addition, by replicating the RTW results, we also validated the developed methodology of fit evaluation that makes use of appropriately made adjustable pants as a test garment.

To explain the observed variation in the pant-body percent differences, one must consider the mutual impact that body and pant 3D surfaces can have on each other. Fluctuations in a variable can be due to the specific individual shapes of the analyzed body sections. Because this style of pant is made to fit smoothly over the largest protrusions on the body and hang approximately vertically from the abdomen in front and the hip in the back, ease values of the sections above the abdomen, where the pant follows the body shape, should be different from the ease values below the abdomen, where the pant stands away from the body surface. Cross sections taken from a body scan with a horizontal plane above the hip area have an oval shape; differences in the lengths of the boundaries (i.e., circumferences) of the body and the pant ovals may be the same (fitted pant), positive (loose pant), or negative (tight pant), producing zero, positive, or negative circumference pant-body percent differences, respectively. A positive circumference difference within certain limits is generally an indicator of good fit. However, a small negative percent difference in the circumferences sometimes occurs when the pant compresses the soft body tissue (e.g., at the abdomen) without causing any discomfort and also can provide better fit at the same time. Small negative percent differences of the surface areas and volumes may also be a result of compressed soft tissue. Negative surface area differences may also be observed for sections in which there is a deep indentation in the body (e.g., indentation of the waistline, the underwear elastic bands, or body tissue folds) and the smooth surface of the overlaying pant is smaller than the surface of the body. Therefore, small negative differences should not be considered as indicators of bad fit, especially in areas of

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compressible soft body tissues. A positive difference in the circumferences is associated with a positive difference in the slice areas of the corresponding cross sections if donning of the pant does not change the shape of the body inside (e.g., in the case of abdomen compression), and the pant wraps around the body, causing the pant cross section to enclose the body cross section fully.

In sections below the abdomen, the surface area of the body may be larger than that of the pant when the convex curve of the body below the abdomen is large enough and results in a negative pant-body difference in the surface area. In the section between the hip and the thigh, the surface area of the body may be either larger (which will always be true for skirts) or of the same order as the surface area of the pant, causing negative or small surface area pant-body differences, whereas the volume differences of the corresponding section are highly positive. Variation of measurements for the sections below the abdomen level may be related to the variation in hip and thigh depths (front-to-back across body dimensions) and their position with respect to the protrusion of the abdomen and the buttocks from the frontal plane. For example, a large negative circumference difference can occur in combination with positive slice area difference in the cross sections around the crotch area, where the pant cross section is still an oval, whereas the body cross section may be shaped as a kidney or may be separated in two small ovals; then the boundary length(s) of the body cross section is (are) larger than the boundary of the surrounding pant. In our experiment, large positive differences in the waist area sometimes occurred because of the lack of waistband in the adjustable pant, the firmness of the fabric, and the thickness of the Velcro closures that prevented the pants from clinging closely to the waist. This problem was more evident for participants with high HWCR, where the deeply indented waistline was not only difficult to fit exactly with the pants but also undesirable to fit (for aesthetic reasons).

The established general pattern of the percent differences to increase from the waist down to the abdomen, hip, and thigh (see Table 2) can be used as an indicator of good fit. This pattern in combination with the known difference in the increase rates of the pant-body percent differences of circumferences, slice areas, surface areas, and volumes can be used to evaluate goodness of fit automatically.

Size and Shape Dependence of Wearing Ease: Implications for Grading

Further objectives of our study were to investigate the possibility that the pant-body percent differences depend on body size and shape. The results did demonstrate an overall tendency of the pant-body percent differences to correlate negatively with size, even though these differences were not statistically significant for the most part. When such an association is established, it can be used to build an appropriate dependence model of the pant-body percent differences on size and calculate the measurements of the pant that will fit specified body measurements well. The size-dependence model should be chosen as the function that best fits the experimental data (e.g., linear, quadratic, exponential, etc.).

Similarly, should a shape dependence of the pant-body percent differences be discovered, this would mean that to fit a garment well, ease values could be calculated differently for different body shapes. The results of the study did not demonstrate any clear shape dependence of the pant-body percent differences, even though for most variables there was an overall tendency of the *medium*

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shape group to have the lowest average percent differences, followed by the *straight* and the *curvy* groups. A body shape definition other than hip-to-waist circumference ratio may have allowed detection of shape dependence. Our body shape definition was extremely simplified and omitted any direct involvement of the height dimension of the lower torso. By adjusting the test pant for torso height, we effectively controlled for that dimension: The waist, abdomen, hip, and crotch levels of the adjustable pant matched the corresponding waist, abdomen, hip, and crotch levels of the body exactly.

Any established differences in the pant-body percent differences between shape/size groups can be used for construction of shape/size dependent grading rules for garments. For example, at each body location, wearing ease amounts can be calculated for each body size according to the pant-body circumference percent difference found to ensure good fit for that body size at that body location. Surface area of the pant is directly connected to the area of its pattern, and therefore, in the pattern-making process, the circumferential wearing ease amounts can be calculated so that the surface area "ease" amounts are in accord with the results for the surface area pant-body percent differences that provide good fit.

Different size dependence approximation models can be used for different variables. Also, the size model does not need to be the same for different shape groups. Determining the best size approximation model is crucial for constructing a good garment sizing system. A possible shape–size interaction in the ease values model would lead to a complicated sizing and grading system. The size and grade rules would be different for each of the shape groups, and within each shape group the size dependence might be different. A system that includes so many different combinations of hip and waist ease values is quite complicated but its implementation would be possible in cases where pattern grading is computer aided.

To calculate the correct ease amounts, other factors also need to be taken into account. For example, according to preliminary results of a study investigating body measurement changes when a person is seated, the differences between the hip circumferences of the seated and the standing body increase rapidly with size, whereas the crotch length decreases (Ashdown et al., 2003; Petrova, Ashdown, Loker, & Schoenfelder, 2003). Inclusion of ease values designed to provide mobility at the hip would result in much higher ease amounts than those calculated with any of the size dependent methods considered above. However, full inclusion of the large ease values determined by the changes of the body circumferences after sitting may not be necessary because of interactions resulting from the decrease of the crotch length with size. Other factors that need to be taken into account include variations in the malleability of the body, the levels of garment pressure that are consistent with comfort and good fit, the properties of the fabric, the cut of the garment (grain), the style ease, and so on. Ease values calculated in this manner should be used to determine the inter-size interval of a sizing system: The interval between two sizes needs to be smaller than the sum of the ease amounts predicted for these sizes, ensuring that for a body with a measurement anywhere on the interval, there will be a garment in the size range that will provide good fit.

Even though most of the shape/size dependencies observed in this study were not statistically significant, theoretical propositions about the usefulness of such dependencies for sizing system construction can be made. The current practice is to create a body sizing system and then apply the grade rules of this body sizing system to a base

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size of the garment for which the ease amounts have been determined based on prior experience. Such a sizing system only captures the fit of the garments for the base size. Using good-fit ease values from data analysis of studies such as the one presented here would give the opportunity to adjust the garment sizing system in such a way that the body of every size is accommodated by an appropriately sized pant. To be successful in providing well-fitted garments, a shape-based sizing and grading system could be used when garments are designed and marketed for specified shape groups if they show shape-based ease dependencies.

The visual effect created by a garment will vary when the same garment is fitted to bodies of different shapes. Bye and DeLong (1994) found that there is a noticeable difference in the visual effect of a design along the size range of a garment. If the target market definition is expanded to include the shape as well as the size category of the customers, both the design and the fit of the manufactured garments may be improved using a shape dependent grading system, thus giving the customers more satisfaction with the fit of the garments.

Example of size dependent grading. The following example demonstrates how, when constructing a garment sizing system, hip ease amounts can be calculated differently by using different forms (referred to as *models*) for the dependency of the pant-body percent differences of hip circumference on size. Generally, such different models can be determined through data analysis of fit studies similar to the one presented here by examining a variety of garment styles and a variety of body types. This example is limited to circumferences only as they have a clear correspondence to the traditional concept of ease and can be easily understood. In more complicated versions, an interpretation of circumference differences could be made based on percent differences of surface areas (which correspond to the surface of the garment patterns), slice areas, and volumes at various body locations.

Consider a hypothetical sizing system with eight body size groups with hip circumference equal to 870 mm for the lowest size group, and a 55 mm increment of hip circumference measurements between each of the adjacent sizes (parameters of this body sizing system were selected arbitrarily). Table 5 presents the calculated pant dimensions at the hip for each size of the above body sizing system using the following three models for the dependence of the pant-body percent differences of circumferences at the hip on size:

Model A: The pant-body percent differences of hip circumference are constant with size (the average of 4.8% of the pant-body percent difference of the hip circumference was used as the constant of the model).

Model B: The pant-body percent differences of hip circumference decrease linearly with size (linear regression).

Model C: The pant-body percent differences of hip circumference vary as a second power of size (quadratic curve).

The constant (Model A) and the coefficients of the linear (Model B) and quadratic (Model C) regressions were calculated using data from all 24 study participants. Model A produces ease values between 42 and 60 mm that increase with size. Model B (observed for many variables in our study) produces approximately the same ease amounts for all sizes in the considered size range. This model corresponds most closely to the current pattern-grading practices. The ease values produced by Model C vary with size, becoming smaller for the middle size range. Depending on the size dependence approximation model

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Table 5
Body Hip Circumferences, Pant Hip Circumferences and Hip Ease for a Hypothetical Sizing System[a] Where the Pant-Body Percent Differences of Hip Circumference Are (A) Constant With Size, (B) Linearly Changing With Size (Linear Regression), (C) Changing as Second Power of Size (Quadratic Curve Estimation[b])

Size-Group Label[a]	1	2	3	4	5	6	7	8
Body Hip Circumference[a] (mm)	870	925	980	1,035	1,090	1,145	1,200	1,255
(A) Model A: Pant-body percent difference for hip circumference is constant with size								
Pant hip circumference (mm)	912	969	1,027	1,085	1,143	1,200	1,258	1,315
Hip ease (mm)	42	45	47	50	52	55	58	60
(B) Model B: Pant-body percent difference for hip circumference linearly decreases with size[b]								
Pant hip circumference (mm)	919	975	1,031	1,086	1,141	1,195	1,250	1,304
Hip ease (mm)	50	50	51	51	50	50	50	49
(C) Model C: Pant-body percent difference for hip circumference as second power of size (quadratic curve)[b]								
Pant hip circumference (mm)	923	975	1,028	1,082	1,137	1,194	1,251	1,311
Hip ease (mm)	53	50	48	47	47	49	51	56

a. Parameters (body hip circumferences for each size, intersize interval, size labels) of this hypothetical sizing system are selected arbitrarily.
b. The idea of regression is to find the parameters of an approximation function (curve) that minimizes the sum of the squared vertical distances from the data points to the curve. The approximation function is a straight line (defined by two parameters) in case of linear regression or a quadratic polynomial (defined by three parameters) in case of quadratic regression.

being used, the calculated ease values will be very different. Therefore, it is very important to establish the correct size dependence model for each variable.

Limitations of the Study

The results for the shape dependence of the pant-body percent differences were inconclusive, possibly because of the simplified definition of shape used for participant selection and shape discrimination. A more detailed shape descriptor than the hip-to-waist circumference ratio may be a better choice for describing the body shape and may also reveal shape dependency of the fit variables.

Several factors prevented us from generalizing the study results. The study was based on a small sample size: 24 subjects representing 3 shape groups with 8 subjects each and 4 size groups with 6 subjects each. The small number of subjects in each group may have prevented us from obtaining results of statistical significance and was probably one of the explanations for the differences between the results of the ANOVA and the Kruskal-Wallis tests.

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The validity of the study was further limited by the fact that only one fit expert was involved in fitting the pants. Securing a second fit expert was impossible with the resources available for conducting this study. The test garment and the research tool (i.e., the body scanner) also presented some technical limitations to the study. The relatively stiff fabric used and the Velcro joins affected the drape of the pants on the body. The pants were also incapable of withstanding the stresses exerted by the body on the pant while sitting, which limited the fit testing to a standing position only. To test fit in the seated position, the construction of the test pant needs to be improved, or ease values necessary to accommodate the seated body need to be determined using a different method.

Using a body scanner as a measuring tool has some limitations, such as the time needed to manually prepare and measure the scans and the difficulty of reproducing the body position exactly in consecutive scans for comparison (Brunsman, Daanen, & Robinette, 1997). However, the advantage of obtaining a great variety of linear, 2D, and 3D body measurements with high precision makes the use of body scanners highly desirable for fit and sizing studies and justifies the efforts of researchers to develop the applications of the scanning technology.

Conclusion and Future Work

An objective of this study was to identify the wearing ease values that would reflect good fit of a specific style of pant. Wearing ease, the difference between the pant and the body, was investigated by means of a measure called pant-body percent difference, which was calculated as the pant-body difference expressed as a percentage of the corresponding body measurement. Measurements of the circumferences, slice areas at the waist, abdomen, hip, and thigh, and the surface areas and volumes of the sections between consecutive body slices were taken for the pant and the body. Measurements were made using a 3D whole body scanner as a tool. To ensure that the measured pant-body percent differences reflect good fit, we used a specially developed adjustable pant, which was fitted to each of the test subjects. We investigated the possibility for size and shape dependence of the percent differences by recruiting subjects of different shapes and sizes. The results of this exploratory study suggested that the pant-body percent differences might decrease with increasing size. We demonstrated the implications that size dependence of percent differences could have on creating sizing systems and pattern making.

A study design employing more subjects may yield more robust and statistically significant results for the calculated ease values. Shape dependence was not established for our definition of body shape (hip-to-waist circumference ratio). Exploration of variety of body shape definitions may uncover a shape measure that has impact on the pant-body percent differences and therefore calls for shape dependent sizing systems. An examination of the ease values required for comfort when the wearer is in different body positions will also contribute data for developing data-driven sizing systems.

The use of the body scanner for sizing and fit studies is at an early stage of development. Although it is a powerful tool that has potential to change the way we measure the fit of clothing, much work remains to discover the most effective use of this tool. Validation of scan measurements for apparel applications and for research studies needs to be investigated in more detail.

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