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Measuring Movement of Denim Trousers for Garment-Integrated Sensing Applications

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Abstract—**The movement of everyday garments over the body surface during wearing often presents a problematic source of noise or error for garment-integrated wearable sensors. This paper describes early results of an assessment of the impact of body location and garment ease on movement of the garment over the body surface. The method implemented uses a running mannequin with a repeatable gait cycle as the source of humanoid motion, and measures the movement of a set of custom-graded denim trousers in 5 ease amounts over the mannequin's surface during the gait cycle. Initial results show consistent patterns of displacement over the body surface.**

I. Introduction

One of the most significant obstacles to pervasive, everyday wearable monitoring of a human body is the tradeoff between comfort of the user and accuracy of embedded sensor signals. Many of the factors that influence the comfort of a worn garment are directly at odds with the variables that promote good sensor signals: factors like tight mechanical coupling of the sensor to the body part, or buildup of moisture between the sensor (in the case of electrodes) and the skin.

In some use scenarios, such as medical monitoring, comfort compromise on the part of the wearer can be an acceptable solution (anyone who has worn a Holter-type heart monitor can attest to this). However, as the potential for body sensing extends beyond medical practice into less-critical application areas like emotion sensing, context awareness, or device interface, comfort compromise becomes ever-more-detrimental to the ultimate adoptability or attractiveness of the device. Even within crucial medical or therapeutic applications, patient compliance can be closely correlated with usability or wearability of the device.

Previous research has considered a variety of approaches to measuring and compensating for movement noise, but to date the impact of comfort-related garment parameters on the movement of a garment over the body surface has not been studied. Here, we present early results that use a novel technique to measure the movement of a garment over the body, in an investigation of the impact of garment ease on movement in a set of denim trousers.

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II. Background

The most common approach to managing movement noise in wearable sensors is to prevent the noise through tight mechanical coupling, by attachment of the sensor to the body using elastic, straps, adhesive, or a skin-tight garment [1] [2] [3]. Poor mechanical coupling results in movement or slippage of the sensor over the body surface (particularly dramatic in garment-integrated sensors), which generates inconsistency or error in the sensor signal (assuming the "best case" signal is captured when the sensor mimics exactly the body surface). In situations where mechanical countermeasures are impractical or do not provide a clear enough signal, a few other techniques have emerged to detect and/or counteract the generated error or noise. In electro-dermal sensing, research has explored using inertial [4] or optical [5] sensors coupled with the electrode to detect and filter movement error, and using capacitive electrodes in place of the traditional conductive contact electrodes (as they are more resistant to movement noise) [6]. In stretch sensing of body position and movement, redundant sensors have been explored as a means of improving accuracy in a noisy and/or imprecise sensor configuration [7].

A portion of the literature in inertial sensing takes an approach that accepts the wearability constraints inherent to everyday clothing. This approach uses a very limited number of sensors with ambiguous and changeable forms of body attachment (such as an accelerometer-equipped mobile phone in a pocket) and seeks to extract the most activity information possible from the given input. This approach has been successful in identifying coarse activity classes [8] [9] for use in ubiquitous computing applications, but is less well-suited to fine-grained activity recognition or specific monitoring of body postures and movements.

Measurement of garment movement has been studied in less depth. We have previously demonstrated the impact of garment design parameters such as garment style and wearing ease on the signal of an embedded sensor, using a skin-tight sensor as a point of reference [10]. Mattmann et. al [11] have demonstrated the use of a motion-capture system to measure the stretch of a skin-tight garment over the torso during motion.

Measurement of garment movement is also of interest to the graphics and animation communities. A few studies have used motion capture of fabric swatches [12] or video analysis of physical garments [13] for use in virtual reproduction of movement and/or appearance characteristics. These approaches are generally more concerned with the visual appearance of realism, rather than seeking to accurately reproduce the measured or recorded movement.

In the experiment described here, the movement of garments of specific dimensions relative to the body surface was recorded, and the Euclidean distance between body and garment measured in 3D. This distance can be interpreted as a coarse-grained measure of "error", or displacement between the desired measurement (a given point on the body surface) and the actual measurement (the x/y/z position of a corresponding point on the garment). This kind of measurement is divorced from a specific type of sensor: although it relates most directly to inertial, position, or motion sensors, the effects of displacement of the garment from the body surface impact a wide variety of body sensors (from electro-dermal sensors to infra-red sensors to acoustic or ultra-sonic sensors and beyond).

III. Method

A. Motion capture

Measuring the position in space of a point on a garment and a corresponding point on the body underneath the garment requires one of two things: either the ability to either monitor the movement of both points simultaneously, or to reliably and precisely repeat a body movement so that it can be measured with and without clothing independently and the measurements subsequently compared. The former is not currently readily possible without affecting the movement of the garment over the body surface, because most accessible means of motion capture require either line-of-sight between markers and cameras, or a bulky/heavy sensor pack. The latter (precise repetition of movement) is practically impossible for human subjects. Here, we use a humanoid substitute: an animatronic running mannequin (Cyberquins, Ltd., UK). The mannequin's gait cycle is precise and repeatable, and allows measurement of the movement of specific measured points on the body surface independent of corresponding points on the garment surface. The two measurements are then compared in post-processing.

To measure movement, we use the SMART-E reflective marker-based motion capture system (BTS Bioengineering, Italy). This system uses lightweight retroreflective markers (ours are 1cm in diameter) that are adhered to the surface of the body or garment, with negligible impact on the movement of the textile. The system outputs XYZ coordinates of each marker at 60 Hz, and reports error of <0.2mm on the volume measured here.

Markers are arrayed over the surface of one half of the symmetrical garment during data collection, at intervals that correspond to body positions marked in paint on both body and garment. During body measurement, markers are pinned directly into the foam surface of the mannequin. Two reference markers are used in addition to the experimental array: a marker on the mannequin's heel, which is used in synchronization of the collected signals in cases where multiple datasets must be collected, and a marker on the mannequin's torso (a stationary body location), the movement of which is subtracted from all other markers to filter out vertical "bounce" caused by the mannequin's slightly unstable side-mount. To measure movement of the garment over the body, the Euclidean distance between points is calculated for synchronized signals.

B. Test garments

The test garments used here were all constructed from the same bolt of denim (100% cotton twill, 12.5 oz). A base pattern, fitted to the mannequin, was initially developed (size "base") using a common drafting procedure [14] for men's trousers. This pattern (depicted in Figure 1), was modified to include extra rise/fullness in the posterior, to allow the mannequin's hip to flex unimpeded (impeding the motion of the mannequin can damage its mechanism).

The base pattern was then graded into five sizes using a custom grade (nested in Figure 1), which increased the waist and hip circumference by 1" for each successive size. This increment was tapered down to a ¼" circumference increase at the ankle to maintain the garment style. These sizes are named for their ease increase from the base size at the waist/hip: Base, +1, +2, +3, and +4.

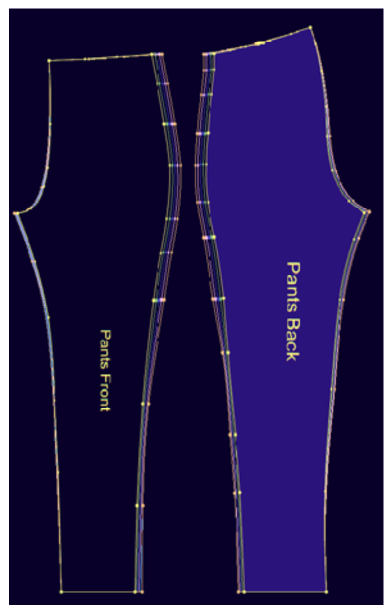

Fig. 1. Test garment pattern grade (nested)

C. Experimental procedure

Marker locations at 19 points on the mannequin's left leg were captured as a baseline measure. The corresponding points on the pants surface (as measured by proportion of circumference and length) were similarly captured, during periods of approximately 20 seconds (eight "steps" for the mannequin). In addition, the two reference markers described above were affixed directly to the mannequin's body, to ensure consistent placement during all trials. Trousers, mannequin, and markers are depicted in Figure 2.

The 3D position of the waist reference marker was

Fig. 2. Test garment, mannequin, and marker locations

subtracted from each test marker, and the Euclidian distance between marker pairs (body-garment) was calculated. This distance was averaged over the entire data collection period to arrive at an overall mean "error" (displacement) measurement.

IV. RESULTS

The overall results for 5 sizes with 19 markers each are shown in Figure 3. As seen, there were consistent patterns in magnitude of error over the marker set, but less consistent patterns of error between sizes.

Because of the wearing ease in all garment sizes, the denim fabric is free to buckle and move over the course of the gait cycle. Although the markers are placed in consistent locations, the forces experienced by these locations are highly variable: in one garment a given marker may be pushed close to the body and remain there throughout the gait cycle, where in another garment (or even another trial of the same garment) the same location may cycle toward and away from the body as a fold forms and flattens.

However, in all sizes, the markers at the waist (markers 2-6) showed distinctly lower amounts of displacement. These markers are held against the body by the elastic waistband of the trousers, so the majority of displacement error comes from slippage of the garment during movement. This slippage is most dramatic in the larger sizes, where the waist and hip contain more ease and the garment can slip further without reaching maximum extension of the elastic.

Markers 7-11 surround the hip and buttock areas. This is a location of complex movement as the bifurcated legs of the trousers experience opposing forces. Markers at the front hip in particular are highly prone to occlusion, as the folds that form in that location are the deepest in this experimental setup. Markers 12-14 are located at the mid-thigh: in these trials they experienced slightly decreasing amounts of displacement from front to back.

At the calf, markers 15-17 experienced a fairly consistent amount of displacement. However, at the ankle, there was a dramatic increase in displacement at marker 18 (front ankle), decreasing from front to back toward marker 20, which shows a similar amount of displacement as the calf-level markers. This effect is caused by the relatively larger difference in circumference between body and garment at the ankle. The test garments used here are drafted to approximate the shapes of everyday garments, and therefore do not conform to the tapering of the ankle. During the gait cycle, the back of the pants leg remains in contact with the mannequin's ankle fairly consistently, which pulls all of the excess circumference to the front of the ankle. For this reason, marker 18 rides much farther from the body surface

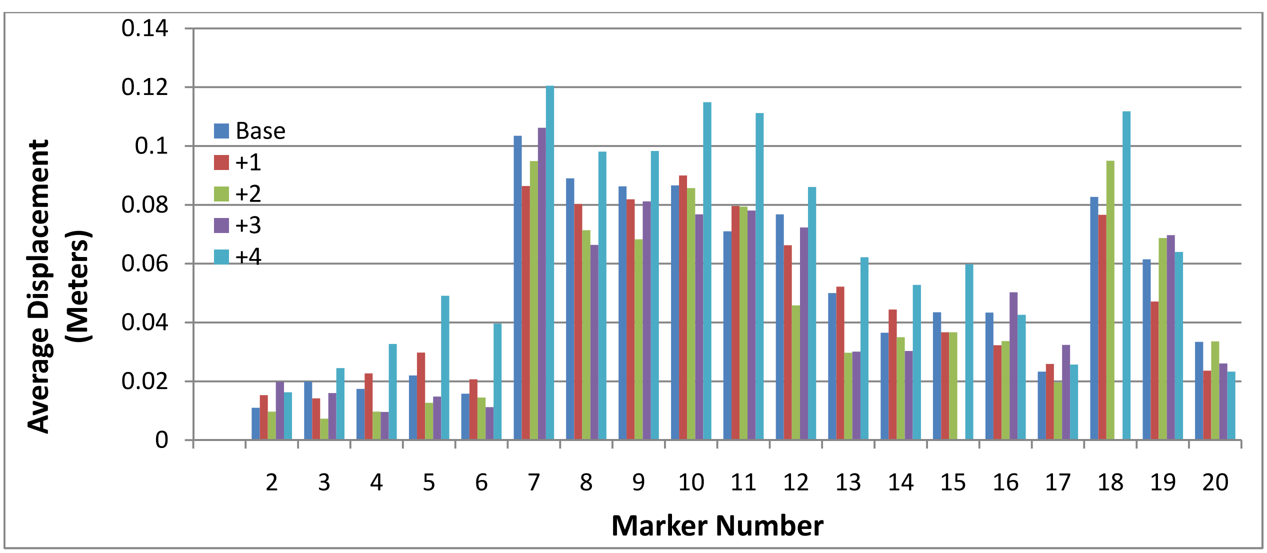

Fig. 3. Overall average displacement for each marker in 5 sizes (measured in meters)

than marker 20.

This distribution of error is illustrated in Figure 4, which shows the error of the base size garment.

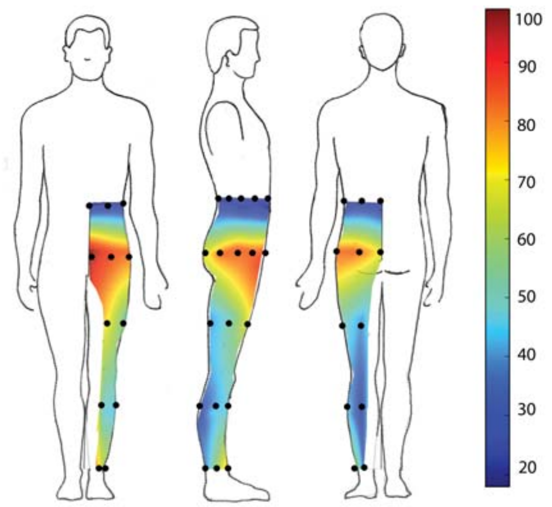

Fig. 4. Displacement of Base size trousers over the body surface in mm, averaged over the gait cycle

V. CONCLUSION

The assessment of movement error (displacement) in this experiment is performed at a very coarse level: overall average displacement over the entire gait has revealed patterns relative to body location, but it is clear that more detailed analysis of movement characteristics must be performed. In these experiments, besides body-location factors, other factors (such as ease amounts, inconsistency in buckling behavior, displacement due to donning/doffing or initial garment position, and garment slippage during the test cycle) were likely at play. Future work includes more fine-grained analysis of the quantity and characteristics of garment movement in each marker location, as well as broader analysis of movement of garments in this size grade, but fabricated from textiles with different physical properties (weight, stiffness, etc.).

While the coarse analysis presented here provides guidance to designers of wearable sensors as regards placement of sensors over the body surface, it is hoped that more detailed analysis will yield insight into possible strategies for avoiding or compensating for movement error in a sensor signal.

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