Knit Stretch Sensor Placement for Body Movement Sensing

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ABSTRACT

Motion capture technology is widely used in movement-related Human-Computer Interaction, especially in digital arts such as digital dance performance. This paper presents a knit stretch sensor-based dance leotard design to evaluate the locations where the sensors best capture the movement on the body. Two studies are undertaken: (1) interviews to determine user requirements of a dance movement sensing system; (2) evaluation of sensor placement on the body. Ten interviewees including dancers, choreographers, and technologists describe their requirements and expectations for a body movement sensing system. The centre of the body (the torso) is determined to be the area of primary interest for dancers and choreographers to sense movement, and technologists find the robustness of textile sensors the most challenging for textile sensing system design. A dance leotard toile is then designed with sensor groupings on the torso along the direction of major muscles, based on the interviewees' preferred movements to be captured. Each group of the sensors are evaluated by comparing their signal output and a Vicon motion capture system. The evaluation shows sensors which are constantly under tension perform better. For example, sensors on the upper back have a higher success rate than the sensors on the lower back. The dance leotard design was found to capture the movements of standing lean back and standing waist twists the best.

CCS CONCEPTS

• **General and reference → Design**; **Evaluation**; **Experimentation**; • **Computer systems organization → Sensors and actuators**; • **Human-centered computing → User studies**; **Laboratory experiments**; **User centered design**; **Interface design prototyping**; • **Applied computing → Performing arts**.

KEYWORDS

E-textiles; Knit Stretch Sensor; Motion sensing; User-centered design

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1 INTRODUCTION

Digital performance [3] is a form of live art that integrates computer technologies and techniques into a live art performance. Over the past several decades, computer technology has been widely used in the performing arts. Artists have enhanced their artistic performance by combining computer technology, multimedia, and tangible interaction in dance [2, 16, 19], theatre [7], and performance art [22, 23] . Particularly in dance production, the addition of computer technology gives artists more creative space [6, 20, 21]. The computer techniques and software such as motion capture system and advanced animation are often used to present a virtual dancer's animation [15, 18], which allows artists to invent and improve their creative expression through body language. It also gives the performer the ability to interact with audiences during the performance with visual, sound, virtual displays, and other effects commonly used in digital production as the output [3].

In dance performances where body language is the primary mode of expression, motion-sensing is particularly essential. Motion capture systems[4] and wearable technology [14] are currently the primary methods for motion sensing. Among them, motion capture systems are mostly vision-based systems with high-resolution cameras, while wearable technology places sensors directly on the body for data collection. Vision-based systems are usually costly, require complicated installation and setup, and are easily affected by the environment. Wearable technology can offer a better solution by carrying the sensors on the body. However, to wear several hard electronic sensors on the body while dancing is not ideal for the performer. It not only restricts dancer movements but also increases the rate of injury.

Instead of wearing inflexible electronic equipment on the body, e-textiles provide a solution for sensing human movement data next to the skin. E-textiles sensors can be integrated into the garment as a soft, lightweight, and invisible form with fabric-based strain sensors

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[10, 24, 27] becoming more prevalent in e-textile applications for body movement [5, 13]. Stretching is an attribute possessed by knitwear which both enhances the comfort of clothing, and allows for flexibility in shaping. This fits the needs of wearable sensing perfectly as knitted stretch sensors can be placed on the body tightly in a comfortable way [9, 11]. This means data can be collected closer to the body with the technology remaining hidden. The textile sensor is not only flexible but also can be integrated into clothing, which is close to the body without restricting movement. However, for garment sensing system, the location of the sensors on the body [25] becomes the key to track movements. It needs to be considered and design based on the motion and application.

Our interest is in the design of a textile-based tangible system for dance performance. Previous work has focused on individual sensor design [12] and reliability testing [11], but we are interested in placing those sensors on the body. First we need to determine the system requirements including what dancer actions should be sensed and what parts of the body should be tracked while dancing. To determine this a qualitative interview study is carried out with dancers, choreographers, and technologists. Building on the results of the interviews, we then examine where to place the sensors. To do so, we design a dance leotard to test which sensor locations best capture the desired movements.

2 STUDY I - EXPERT INTERVIEWS

To gather target users' ideas, requirements, and expectations of various aspects of digital dance performance. We conducted a qualitative interview study with dancers, choreographers and technologists.

2.1 Method

Ten participants who were professional dancers, choreographers, and technologists (including an author of this paper) participated in the study. The interviews were semi-structured with two sets of open questions. For participants who have a dance background, we asked about their experience, dance style, the characteristics of the movements, clothing, materials, colour, which part of the body to sense, and common basic movements. The questions for technologists focused on their experiences with motion-sensing projects, challenges when designing textile interfaces, and suggestions for textile sensing system design. For interviewees who had experience in both dance and technology, we included all interview questions. Interviews were carried out either in-person or online, each lasting between 45 to 90 minutes and were video recorded. The video data was transcribed manually and analyzed using thematic analysis[1] with MaxQDA.

2.1.1 Participants. As Table 1 shows, most participants had backgrounds in multiple relevant areas. For example, P5 is a choreographer who also works with e-textile technologies. All of the technologists have experience in movement-related textile projects.

2.2 Results

2.2.1 Technologists. The technologists all had a similar background in researching e-textiles within the field of human-computer interaction. Participants shared their experience of working with dancers, designing for the body, and development of motion-related projects. They reflected on their choice of materials and types of sensors, which were generally based on the creative concept and requirements of the project. Once those are established, they then consider and test the electrical properties of the selected materials and sensors. In designing e-textile sensing systems, a sensor's robustness and obtaining a reliable, consistent output are the most challenging aspects, e.g. "I think often [about] the robustness of it - the technology can make it quite challenging"(P8), "to get the same results with the same movements"(P10). Beyond stretch sensors, participants also used switches [17], tilt sensors [26], and capacitive sensing [8] for motion sensing in their projects.

Table 1: The background of interviewees

Participant NO.	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Dancer	✓	✓	✓	✓		✓				
Choreographer			✓	✓	✓	✓				
Technologist					✓		✓	✓	✓	✓

2.2.2 Dancers and Choreographers. All the dancer and choreographer interviewees work in contemporary dance / modern dance. They described this dance style as incorporating many other dance styles and containing a lot of floor work. Compared with dance styles such as ballet, contemporary dance allows for more freedom in the interpretation of the movements. The movement characteristics in contemporary dance are varied, e.g."It has quite a lot of different dynamic quality it could be very slow it could be really fast could be very energetic"(P2), "it could be any characteristic"(P3). The choreographer has the responsibility to decide what style and quality of the movement is in a dance performance piece.

As for the clothing, participants emphasized the comfort and flexibility of the clothing used in rehearsal, e.g. "should be comfortable or just you know movable"(P4). Participants reported that they prefer layers and dark colours, e.g. "usually long sleeves because it's about - you know - rolling on the floor"(P2). This differs from the dance performance where the costume depends on the choreography style and creative direction.

The centre of the body was mentioned many times as an essential part of contemporary dance. Dancers treat the centre of the body as to where all the movements come from, e.g. "dancers definitely think of, like, their torso as where the movement comes from and like they initiate from their spine and from their core"(P5). As such, the centre of the body: torso, spine, back, and core, are the parts of the body of primary interest for dancers and choreographers for motion tracking while dancing. For a better understanding of contemporary dance movements, participants were asked to perform the basic movements around their interested part of the body. Roll down, lean back, side bend, C-curve, and back arch were mentioned and performed by participants as the basic movements around the torso, e.g. "we do a lot of like rolling through the spine right to stand up and like rolling down"(P2), "I'm arching my back and this is curve... I'm creating shapes like c shapes each way"(P4). Participants described the essential aspects of these movements and also assessed and analysed the potential locations of the body where stretching occurs while performing these movements.

2.3 Discussion

From the interviews, we found crucial suggestions and requirements for designing a sensing system for dance performance. The sensors' electrical and material properties play a key role in the sensing system. In order to accurately monitor body movements, the sensors need to be robust and have consistent and repeatable readings otherwise they can interfere with the creative expression of the digital dance performance.

Through the interviews, we better understood the features of contemporary / modern dance. Contemporary dance is more interpretative than other styles as the repertoire of movements allow more freedom while also incorporating other elements from other dance styles. Thus, this dance style fits well within interactive digital art performance and with more improvisational performances. From the dancers' preferences and requirements in leotards particularly for rehearsals, we should consider designing a dance leotard with long sleeves in dark colours. The dance leotard is the most commonly worn clothing for dancers. It not only needs to fit the body perfectly but it also allows for full range of motion without restriction. They are ideally tight against the body to prevent unwanted exposure of the body when the costume is too loose. As for which area of the body to prioritize tracking with a sensing system, the torso is clearly identified as the preferred location in order to track the dancer's movement.

3 STUDY 2 - SENSOR PLACEMENT

Building on the results of the interviews, we designed a leotard with knit stretch sensors to measure torso movements as can be seen in Figure 1. Along with fitting within the aesthetic requirements of the dancers and choreographers, the leotard is used to address the reliability and robustness concerns that the technologists expressed. In particular, we examine how the performance of the stretch sensors measuring body movement is affected by the location of those sensors on the body.

Figure 1: The silver-plated conductive fabric: Technik-tex P130B, the knit stretch sensor-based dance leotard and detail of bonded sensors.

3.1 Dance Leotard Design

A long-sleeve leotard was constructed from black Eurojersey fabric. The garment is made for women who wear UK size 8 (EU 36, US 6), but it fits UK sizes 6-12 (US 4-10/ EU 34-40) as the material is stretchy. Sensors were placed along the torso emphasising the spine, back muscles, and abdominal muscles. Multiple sets of sensors were placed close to each other to allow for a comparison of whether a subset of sensors provides better performance. Photos of the sensors, which are metallic stripes of conductive fabric, can be seen in Figure 1 and graphically in Figure 2. Each group of sensors is placed to follow the direction of the underlying muscles that would be used for a particular set of movements: a group of long sensors along the spine are designed to capture the movement of the spine; four groups of two sensors cross each other around the waist aim to capture twisting from two directions with a piece of non-conductive fabric bonded between two sensors as electrical insulation (see the enlarged photo in Figure 1). In the centre front, a long sensor covers the front zipper and secures in place at the neck using a press-on snap. Finally, four groups of short sensors placed on each side of the front chest and upper back to capture the movement of the upper torso.

For the construction of the stretch sensors, we chose to use a commercially produced silver plated conductive knit fabric, Technik-tex P130B (Figure 1), as it has been found to be suitable for small-scale movement sensing [11]. This material has 78% polyamide and 22% elastomer and stretches in both warp and weft directions. All the sensors were constructed with the same width of 20mm using Technik-tex P130B. We used a bonding technique with one layer of bonding to attached the sensors to the leotard as it provides a secure attachment to the garment while increasing sensor output stability without restricting movement [12].

3.2 Method

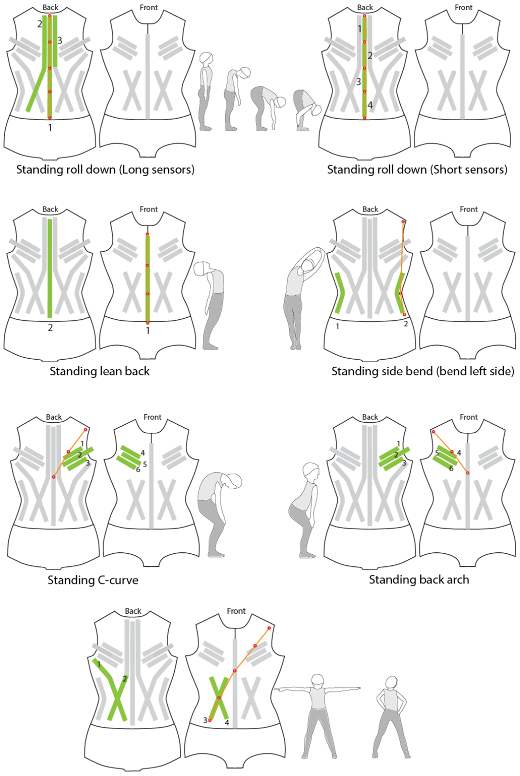
To evaluate the performance of the sensors in dance movements, we use a Vicon motion capture system to capture the movement data as a baseline for comparison with the sensor data. A set of movements and corresponding marker placements were designed for data collection and analysis.

3.2.1 Movement Capture. We chose a set of movements that dancers and choreographers mentioned in the interviews as basic movements focusing on the torso. As Figure 2 shows, a set of six movements were captured all while standing: roll down; lean back; side bend; C-curve; back arch; and twist. The standing roll down was captured in two iterations, each iteration with a different set of sensors. For each movement a corresponding set of reflective markers were placed along the body and a specific set of stretch sensors were activated and measured. This was so movements and sensor performance could be analysed in isolation. For example, only the sensors along the spine were electrically connected for one of the standing roll downs. Because of the symmetry of the body, the movement of the standing side bend and standing waist twist were captured only for one movement direction, but the sensors on both sides of the body were connected. For example, the movement of the standing side bend only bends to the left side, but both the sensors on the left and right side were recorded. The highlighted strips in Figure 2 identify which sensors were used for each measurement.

The motion capture system was used to measure the change in the leotard and underlying body shape throughout the movement. Reflective markers, shown as highlighted circles in Figure 2, were placed along the stretched muscle to get the approximate change in length that occurred throughout the movement.

Table 2: Each long sensor's correlation coefficient in the movement of standing roll down. Each sensor's correlation coefficient in each participant calculated as the median of stretching and relaxation portion across 30 cycles. The result with a high correlation coefficient with an expected positive or negative value is shown in bold text. The cells with grey backgrounds highlight the failed sensors.

Participant NO.	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Sensor 1 (Stretch)	-0.381	-0.299	0.861	0.103	**-0.787**	**-0.738**	-0.192	-0.326	-0.314	0.905
Sensor 1 (Relax)	0.452	0.415	0.312	-0.130	-0.604	-0.519	**-0.847**	-0.499	-0.291	0.779
Sensor 2 (Stretch)	-0.337	-0.430	0.916	0.091	**-0.759**	**-0.723**	-0.420	-0.065	-0.438	0.679
Sensor 2 (Relax)	0.599	0.166	0.582	-0.060	-0.667	-0.461	**-0.858**	-0.410	-0.24 1	0.362
Sensor 3 (Stretch)	**-0.840**	**-0.848**	0.660	-0.678	**-0.891**	**-0.841**	**-0.797**	-0.365	**-0.898**	**-0.757**
Sensor 3 (Relax)	**-0.820**	**-0.929**	-0.119	**-0.796**	**-0.936**	**-0.753**	**-0.964**	**-0.750**	**-0.818**	**-0.915**



Standing roll down (Long sensors)
Standing roll down (Short sensors)
Standing lean back
Standing side bend (bend left side)
Standing C-curve
Standing back arch
Standing waist twist (twist to the right)

Figure 2: The connected sensor and reflective marker set up of each movement. The connected sensors show in green, the red dots are reflective markers for the motion capture system, the red line shows the approximate length and changes of the target part of the torso.

Each movement was repeated 30 times by ten participants. Participants were female university students, none of them took part in Study I. Vicon Blade software recorded each marker's position in the X, Y, and Z-axis, while simultaneously a separate Arduino-based microcontroller measured the sensor's electrical resistance. Each activated sensor was electrically connected to the measurement circuit with two safety pins soldered to wires[1]. A button was used to instruct the microcontroller to start and stop recording data. To synchronize the data from the two systems, we covered the button with a reflective marker to record the pressing of the button within the motion capture system. The sensor's raw data was recorded directly from the serial port and then downsampled to the 120Hz for synchronization with marker data from the Vicon system.

3.2.2 Data Analysis. Treating the Vicon data as the ground truth body position data, the analysis looks at how well the electrical resistance of the stretch sensors correlate with the Vicon's capture of the movement of the body. The distance between each consecutive pair of reflective markers along the body are calculated and summed for each movement. The changes in these lengths are treated as the approximate stretch of the body. Then we compare the correlation coefficient between the length of the markers and the electrical resistance of the sensors to examine the effectiveness of the sensors for measuring the body movements.

Two data subsets are analysed for each movement by dividing each cycle of the movement into a stretching and relaxation portion through finding the peaks and troughs of the captured signals. The correlation coefficient is then calculated between each sensor's resistance and the length of the markers for that part of the cycle. The overall metric of the sensor performance for a participant is the median of the correlation coefficient across the 30 cycles for either the stretching or relaxation portion of a particular movement.

3.3 Results

In theory, a sensor's resistance decreases when stretched and increases when relaxed. Thus, if the sensors and markers are moving in the same direction, the change of the sensor's resistance and the length of markers have negative correlations. Ideally, for groups of negative correlations, the correlation coefficient of the sensor resistance and the changes in the length of markers should be close to -1. In contrast, in comparing groups of positive correlation when the sensor length is inversely changing with a movement (such as being on the back during a lean back movement), the correlation coefficient of the sensor resistance and the changes in the length of markers should be close to +1.

On a first pass of the data, we list the correlation relationship between each group of sensors and corresponding markers as can

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[1] https://www.instructables.com/id/Safety-Pin-Crocodile-Clips-for-ETextiles/

Table 3: Comprehensive performance of each group of sensors. The best-performed sensor in each group is highlighted in bold text. Positive/Negative correlation are the relationship between the sensors and markers in the ideal situation. The success rate is defined as the percentage of successes (correct correlation direction) over the ten participants. The correlation coefficient is the median of the overall sensor correlation coefficient over the ten participants, i.e. the median of the values for each row of Table 2 repeated for each sensor.

Movement Name	Sensor NO.	Positive/Negative Correlation	Success Rate (%) Stretch / Relax	Correlation Coefficient Stretch / Relax
Standing Roll down (Long sensors)	1	-	70 / 60	-0.307 / -0.211
	2	-	70 / 60	-0.378 / -0.151
	3	-	**90 / 90**	**-0.818 / -0.819**
Standing Roll down (Short sensors)	1	-	70 / 80	-0.421 / -0.550
	2	-	**90 / 100**	**-0.761 / -0.891**
	3	-	30 / 20	0.738 / 0.471
	4	-	40 / 30	0.527 / 0.670
Standing Lean Back	**1**	-	**100 / 100**	**-0.843 / -0.960**
	2	+	0 / 0	-0.846 / -0.919
Standing Side Bend	1	+	0 /0	-0.940 / -0.929
	2	-	**60 / 70**	**-0.624 / -0.699**
Standing C-curve	**1**	-	**90 / 80**	**-0.843 / -0.834**
	2	-	70 / 70	-0.522 / -0.492
	3	-	50 / 40	0.002 / 0.336
	4	+	20 / 20	-0.748 / -0.748
	5	+	10 / 10	-0.884 / -0.845
	6	+	0 / 0	-0.935 / -0.924
Standing Back Arch	1	+	50 / 40	-0.081 / -0.134
	2	+	30 / 10	-0.732 / -0.702
	3	+	10 / 10	-0.906 / -0.846
	4	-	**70 / 90**	**-0.322 / -0.660**
	5	-	40 / 60	0.506 / -0.326
	6	-	40 / 40	0.483 / 0.448
Standing Waist twist	1	-	0 / 10	0.930 / 0.935
	2	+	0 / 0	-0.947 / -0.923
	3	+	80 / 70	0.642 / 0.606
	4	-	**90 / 90**	**-0.934 / -0.927**

be seen in for the long sensors during a standing roll down for all participants in Table 2. Any results where there is an inconsistent correlation relationship where the correlation coefficient is either not positive or negative as expected is treated as a failed sensor.

In the standing roll down results in Table 2, all of the sensors should have negative correlations with the markers. Sensor 3 works for all of the participants in the relaxation part and nine of the participants in the stretching part. Both Sensor 1 and Sensor 2 failed three times in relaxation and four times in stretching cycles. In most of the cases, Sensor 3 has a set of higher correlation coefficient than the other sensors.

Table 3 shows a summary of all the sensor results for each movement listing the ideal correlation coefficient value, the percentage of successful (non-failed) sensing cycles and the median value of the correlation coefficient across all 10 participants. The bold highlighted sensors performed the best for that movement.

The standing roll down is the only movement performed twice with two different sets of sensors. The short Sensor 2 and long Sensor 3 both on the upper back were best overall, but short Sensor 2 had a higher success rate than the long Sensor 3. Short Sensor 3 and Sensor 4 located on the lower back failed more often than succeeded.

3.4 Discussion

Our first concern was to investigate the sensor failures. Examining the sensor properties during stretching, the sensor's electrical resistance starts to decrease only after around 30% strain [11]. In other words, the sensor resistance and the motion capture markers have a negative correlation only if the sensor is stretched more than 30%. When the movement fails to stretch the sensor beyond this level, the sensor outputs values are inverse to what is expected. This is confirmed in the analysis of the individual movements.

3.4.1 Standing Roll Down. Standing roll down is a core movement in contemporary dance which focuses on the spine. The leotard compares two sensor design approaches: 1) a group of longer sensors extending down the back, 2) a group of short sensors segmenting the spine. The group of long sensors shows the shortest sensor in the group performs best with the other two sensors of similar lengths being similarly poor. The group of short sensors are each the same length, with the short Sensor 2 - placed on the upper back like the best performing of the long sensors - performing the best.

The short sensors with the lowest success rate are located on the lower back and their poor performance appears tied to how a leotard fits on the body. As the lower spine is concave when standing neutrally, the garment does not have a particularly tight fit in this area. This is exaggerated by participants with different heights and torso lengths. For example, on participant P10 who has a short torso, the sensors on the lower back folds on itself when she is in the standing position. For the roll down the sensor is only extended to its initial length, so the sensors are not stretched more than 30% and the results show a failure.

3.4.2 Standing Lean back. The sensor intended to capture the lean back motion is slightly different than the rest of the sensors. It is floating against the body instead of being closer to the skin because it covers the zipper placed underneath. The sensor is grouped with a long sensor along the spine to capture the complementary motion (Sensor 2 of standing lean back in Figure 2). The front, floating sensor works for all participants with a high correlation coefficient in both stretching and relaxation. The paired long sensor along the back performs very poorly, and analysis from the roll down movement confirms this was a poor sensor placement. We would anticipate a complementary shorter sensor on the upper back to better suit the capture of this movement.

3.4.3 Standing Side Bend. Two sensors are placed on each side of the body close to the side-seams to capture the side bend. As the human body is largely symmetrical, we tested only on one side (bending to the left) but connected both sides' sensors. We found the sensor performance depends on the depth of the bending motion, especially for the sensors on the left. The sensor on the left side (Sensor 1) failed for all participants as this sensor was not stretched and sometimes folded on itself during the movement. The results of Sensor 2 shows it does not work for all participants and has a relatively lower correlation than the other best-performing sensors. It may be because the range of this movement is not that large and the sensor is not tight enough against the lower part of the torso. For some of the participants with a shorter torso, the garment is a little bit long, so the sensors on the lower part are not constantly under tension. In this case, the sensor is unlikely to be stretched more than 30% in some of the smaller-scale motions.

3.4.4 Standing C-curve. Standing C-curve is also a smaller-scale movement that stretches the upper back. Sensor 1, 2, and 3 are placed on the back were anticipated to stretch during the move. Amongst them, Sensor 1 performs better than the other two sensors. The direction of Sensor 1 is closer to the course of the movement and is placed on the shoulder blades. Sensor 2, which is longer and goes across the shoulder seam, wrinkles around shoulder affecting the sensor's performance. The position of Sensor 3 was lower under the shoulder blade, where less stretching took place.

3.4.5 Standing Back Arch. The standing back arch can be considered an inverse movement of the C-curve. The same groups of sensors are tested in this movement, with a set of three sensors on the front anticipated to detect stretching. In theory, the sensors performance should be complementary to those useful in the C-curve — as the sensors on the back fail, sensors on the front should work. Sensor 4 is the best-performing sensor among the six, but it has a lower success rate and worse correlation with the motion capture markers than the performance of Sensor 1 in the C-curve movement. As our participants are female, the size of the breast will affect the sensor results as a tighter fit tends towards a better performance. The best-performing Sensor 4 is placed on the upper portion of the chest and worked for most of the participants, but with low correlation coefficients. We conclude that sensors around the chest do not capture this movement well and that another placement may be better.

3.4.6 Standing Waist Twist. A group of cross-shaped sensors around the waist were intended to capture rotational movement from two directions. For the standing waist twist (twisting to the right), we connected four sensors in pairs of crosses on the left-back and right-front. The results show that sensors across the lower back, Sensor 1 and Sensor 2 once again performed very poorly, they all had incorrect correlation relationships. The other two sensors on the front performed as we would expect. Sensor 4 has better results than Sensor 3 as the movement is only in one direction to the right and we would anticipate Sensor 3 to be better at capturing the twisting to the left side.

4 CONCLUSION

These two studies looked at how e-textile tangible interfaces could be improved for motion sensing in live dance performance. A set of interviews gathered feedback from technologists who have worked with this technology along with the system requirements as described by dancers and choreographers. Based on their input, we designed a dance leotard to sense torso movement in contemporary dance. To further improve the reliability and robustness of the generated sensor data, we evaluated how the sensor placement affects the ability to track a specific set of movements core to contemporary dance.

The interview participants confirmed that they would like to use technology to sense their torso movements in dance performance, but that current e-textile systems present challenges in their reliability and robustness. A dance leotard was found to be the ideal form to fit dancers requirements and was also suitable for housing the sensing system. We made a dance leotard with groupings of sensors to capture a set of movements around the torso. The performance of each group of sensors was compared with the tracking of a Vicon motion capture system. We found only the stretched sensors that were under constant tension and stretched more than 30%, adequately captured the movement. Sensors that relax to a point of little to no tension fail to capture any meaningful movement. Furthermore the placement on the body and fit of the garment plays a key role in the sensor performance. The lower back and the chest are not an ideal place for placing sensors to capture the movements explored here as they were the most prone to fit problems. This implies that pattern cutting and garment fit play an important role in the tangible sensing system design.

These studies only examined isolated groups of sensors for a particular corresponding movement. Before the dance leotard can be used for motion tracking of arbitrary movements, further work of combining groups of sensors, investigating more advanced movements, and the design of an integrated, complete sensing and processing system is needed. We believe that the results of this study show the promise of knit e-textile sensors for lightweight and low-cost technology supporting digital dance performance.

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REFERENCES

[1] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative research in psychology* 3, 2 (2006), 77–101. https://doi.org/10.1191/1478088706qp063oa

[2] Courtney Brown. 2019. Machine tango: An interactive tango dance performance. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 565–569. https://doi.org/10.1145/3294109.3301263

[3] Steve Dixon. 2007. *Digital performance: a history of new media in theater, dance, performance art, and installation.* MIT press.

[4] Christopher Dobrian and Frédéric Bevilacqua. 2003. Gestural control of music: using the vicon 8 motion capture system. In *Proceedings of the 2003 conference on New interfaces for musical expression*. National University of Singapore, 161–163. https://dl.acm.org/doi/10.5555/1085714.1085753

[5] Jonny Farringdon, Andrew J Moore, Nancy Tilbury, James Church, and Pieter D Biemond. 1999. Wearable sensor badge and sensor jacket for context awareness. In *Digest of Papers. Third International Symposium on Wearable Computers*. IEEE, 107–113. https://doi.org/10.1109/ISWC.1999.806681

[6] Sarah Fdili Alaoui. 2019. Making an Interactive Dance Piece: Tensions in Integrating Technology in Art. In *Proceedings of the 2019 on Designing Interactive Systems Conference*. ACM, 1195–1208. https://doi.org/10.1145/3322276.3322289

[7] Gesa Friederichs-Büttner, Benjamin Walther-Franks, and Rainer Malaka. 2012. An unfinished drama: designing participation for the theatrical dance performance Parcival XX-XI. In *Proceedings of the Designing Interactive Systems Conference*. ACM, 770–778. https://doi.org/10.1145/2317956.2318072

[8] Carlos Gonçalves, Alexandre Ferreira da Silva, João Gomes, and Ricardo Simoes. 2018. Wearable e-textile technologies: A review on sensors, actuators and control elements. *Inventions* 3, 1 (2018), 14. https://doi.org/10.3390/inventions3010014

[9] Li Guo, Joel Peterson, Waqas Qureshi, Adib Kalantar Mehrjerdi, Mikael Skrifvars, and Lena Berglin. 2011. Knitted wearable stretch sensor for breathing monitoring application. In *Ambience'11, Borås, Sweden, 2011*.

[10] Inpil Kang, Mark J Schulz, Jay H Kim, Vesselin Shanov, and Donglu Shi. 2006. A carbon nanotube strain sensor for structural health monitoring. *Smart Materials and Structures* 15, 3 (apr 2006), 737–748. https://doi.org/10.1088/0964-1726/15/3/009

[11] An Liang, Rebecca Stewart, and Nick Bryan-Kinns. 2019. Analysis of sensitivity, linearity, hysteresis, responsiveness, and fatigue of textile knit stretch sensors. *Sensors* 19, 16 (2019), 3618. https://doi.org/10.3390/s19163618

[12] An Liang, Rebecca Stewart, Rachel Freire, and Nick Bryan-Kinns. 2019. Effect of bonding and washing on electronic textile stretch sensor properties. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*. 121–124. https://doi.org/10.1145/3341162.3343817

[13] Corinne Mattmann, Oliver Amft, Holger Harms, Gerhard Troster, and Frank Clemens. 2007. Recognizing upper body postures using textile strain sensors. In *2007 11th IEEE international symposium on wearable computers*. IEEE, 29–36. https://doi.org/10.1109/ISWC.2007.4373773

[14] Jane McCann and David Bryson. 2009. *Smart clothes and wearable technology.* Elsevier.

[15] W Scott Meador, Timothy J Rogers, Kevin O'Neal, Eric Kurt, and Carol Cunningham. 2004. Mixing dance realities: collaborative development of live-motion capture in a performing arts environment. *Computers in Entertainment (CIE)* 2, 2 (2004), 12–12. https://doi.org/10.1145/1008213.1008233

[16] Tim Murray-Browne, Di Mainstone, Nick Bryan-Kinns, and Mark D Plumbley. 2010. The Serendiptichord: A wearable instrument for contemporary dance performance. In *Audio Engineering Society Convention 128*. Audio Engineering Society.

[17] Jung-Sim Roh. 2014. Textile touch sensors for wearable and ubiquitous interfaces. *Textile Research Journal* 84, 7 (2014), 739–750. https://doi.org/10.1177/0040517513503733

[18] Marc Ericson C Santos, Angie Chen, Takafumi Taketomi, Goshiro Yamamoto, Jun Miyazaki, and Hirokazu Kato. 2013. Augmented reality learning experiences: Survey of prototype design and evaluation. *IEEE Transactions on learning technologies* 7, 1 (2013), 38–56. https://doi.org/10.1109/TLT.2013.37

[19] Thecla Schiphorst and Kristina Andersen. 2004. Between bodies: Using experience modeling to create gestural protocols for physiological data transfer. (2004).

[20] Jinsil Hwaryoung Seo, Michael Bruner, Nathan Ayres, Christine Bergeron, and Alexandra Pooley. 2019. Upwell: Performative Immersion Hybridizing Two Worlds. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 571–575. https://doi.org/10.1145/3294109.3301264

[21] David A Shamma, Renata M Sheppard, and Jürgen Scheible. 2010. Human-to-dancer interaction: designing for embodied performances in a participatory installation. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems*. ACM, 356–359. https://doi.org/10.1145/1858171.1858236

[22] Jennifer G Sheridan and Nick Bryan-Kinns. 2008. Designing for performative tangible interaction. *International Journal of Arts and Technology* 1, 3-4 (2008), 288–308. https://doi.org/10.1504/IJART.2008.022364

[23] Sophie Skach, Anna Xambó, Luca Turchet, Ariane Stolfi, Rebecca Stewart, and Mathieu Barthet. 2018. Embodied interactions with e-textiles and the internet of sounds for performing arts. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. 80–87. https://doi.org/10.1145/3173225.3173272

[24] Takeo Yamada, Yuhei Hayamizu, Yuki Yamamoto, Yoshiki Yomogida, Ali Izadi-Najafabadi, Don N Futaba, and Kenji Hata. 2011. A stretchable carbon nanotube strain sensor for human-motion detection. *Nature nanotechnology* 6, 5 (2011), 296. https://doi.org/10.1038/nnano.2011.36

[25] Clint Zeagler. 2017. Where to wear it: functional, technical, and social considerations in on-body location for wearable technology 20 years of designing for wearability. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers*. 150–157. https://doi.org/10.1145/3123021.3123042

[26] Clint Zeagler, Scott Gilliland, Halley Profita, and Thad Starner. 2012. Textile interfaces: Embroidered jog-wheel, beaded tilt sensor, twisted pair ribbon, and sound sequins. In *2012 16th International Symposium on Wearable Computers*. IEEE, 60–63. https://doi.org/10.1109/ISWC.2012.29

[27] Jun Zhou, Yudong Gu, Peng Fei, Wenjie Mai, Yifan Gao, Rusen Yang, Gang Bao, and Zhong Lin Wang. 2008. Flexible piezotronic strain sensor. *Nano letters* 8, 9 (2008), 3035–3040. https://doi.org/10.1021/nl802367t