Computational Design of Wiring Layout on Tight Suits with Minimal Motion Resistance: Supplementary Materials

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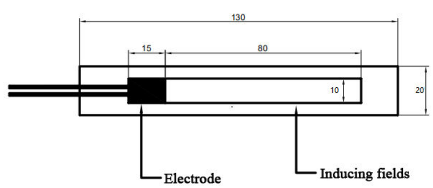
1 STRAIN SENSING SYSTEM

In order to assess the strain deformation in the real world, we developed a strain sensing system to measure the strain deformation at specific positions on the human body. The system comprises 24 flexible stretchable strain sensors (Fig. 1), connected to a circuit board. When stretched, the sensor capacitance increases linearly. The board collects sensor readings and transmits digitized values to an external PC for further data processing.

(a) Sensor Appearance



(b) Sensor Illustration

Fig. 1. Flexible stretchable strain sensor.

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Thickness	Stretch range	Stretching accuracy
0.36 mm	0-50%	0.05%
Linearity	Durability	Operation Temperature
99.9 %	more than 300,000	< 60°

Table 1. Sensor specifications.

1.1 Sensor Specifications

We use the stretchable strain sensors made by Elastech to measure strain deformation. The sensors can be purchased directly from their website [1] at a price of 40 USD per unit.

The soft sensor comprises five layers, from bottom to top: the matrix, the elastic bonding layer, the first conductive layer, the elastic dielectric layer, and the second conductive layer [10]. The matrix is made of an elastic textile material composed of spandex. The elastic bonding layer is the TPU. The first and second conducting layers are composed of GaInSn (a liquid metal) and TPU mixed slurry. The elastic dielectric layer consists of three sub-layers, including guta gum, the dilatant fluid and the thermoplastic elastomer. The dilatant fluid is the starch solution composed of corn starch and water. The mass ratio of corn starch to water is (1.5 - 2):1. For more information about the fabrication and performance of these sensors, please refer to [10].

Key specifications of the sensor is shown in Table 1. The sensor is thin (0.36mm), therefore suitable for integration on the clothes while introducing minimal resistance to human motion. It is not only durable for conducting repeated experiments but also highly accurate, with a resolution of 0.05%. This resolution is small enough to ensure accurate measurement of strain energy in our specific case.

We choose the capacitive sensor for its superior linearity between the capacitance and the strain (Fig. 2). The same sensor was used in a recent work [9] to monitor elbow rotation, where its capacitance demonstrated remarkable linearity as it was stretched during joint movement.

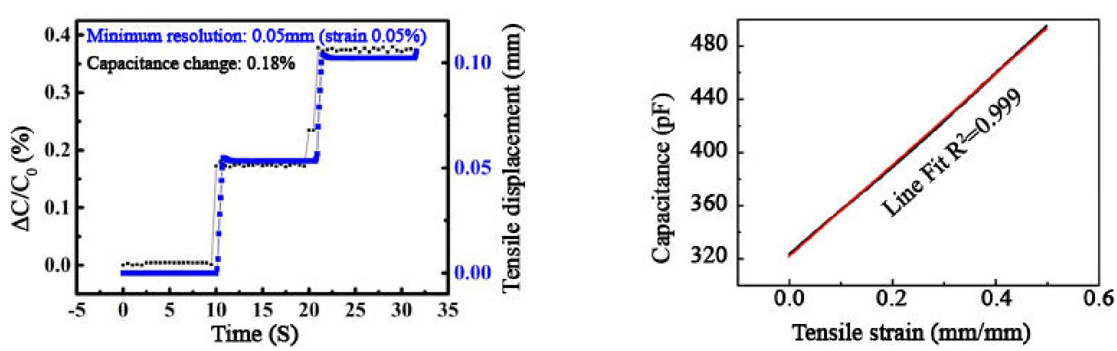


Fig. 2. Sensor characteristics.

[1] http://www.elas-tech.com/product/detail/7.html

1.2 Data Collection & Transmission

As aforementioned, a total of 24 sensors are connected to a circuit board using wires of varying lengths. The maximum wire length is 1.5 meters. The availability of different wire lengths enables flexible placement of the sensors on arbitrary positions of the participant's body surface, facilitating accurate measurement of specific strain deformation magnitudes.

The capacitance value is converted to a digital form within the range of [0, 1023]. The circuit board, provided by the sensor vendor *ElasTech*, transmits these digitalized sensor signals directly to a desktop computer equipped with a Bluetooth dongle. The data transmission occurs at a framerate of 50Hz. The server utilized in this setup features a one-core CPU without GPU support and a memory capacity of 2GB. The operating system installed on the server is 64-bit Ubuntu 16.04.

1.3 Tight Suit & Attachment

We manufactured the tight suit using a fabric blend of 88% cotton and 12% polyester. The surface of the tight suit is fully covered with the hook side of the velcro, while the back of the sensor is covered with the loop side of the velcro. This velcro hook and loop mechanism ensures a secure attachment of the sensor to the desired position on the suit's surface. Throughout our experiment, the velcro maintains its grip without any loosening, even when the participant engages in various activities.

2 SUBOPTIMAL SOLUTION

As mentioned in the main paper, the construction of a Minimum spanning tree on a graph with on-body electronics as vertices and pair-wise (deformation-weighted) shortest paths as edges is a sub-optimal solution. To support our claim, we compared it with the proposed solution based on the Steiner tree problem. As Table 2 shows, the suboptimal solution produces about 10% more deformation energy. Please note that in the suboptimal solution, we compute graph-based shortest paths instead of geodesics as to the best of our knowledge, there are no efficient algorithms available to solve the weighted geodesic problem on triangle meshes.

Table 2. Comparison of deformation energy between the proposed solution (based on the Steiner tree problem) and its suboptimal alternative (based on the Minimum spanning tree) with different numbers of sensors.

	10	15	36
Suboptimal solution (Minimum spanning tree)	88292.37	93262.49	121082.03
Ours (Steiner tree problem)	**81438.84**	**89966.87**	**113983.35**

3 CLOTHING FABRICATION

The process of our clothing fabrication comprises the following procedures.

Preparation of Tight Suits. The tight suit is prepared according to 2D patterns specific to body sizes M, L, and XL. The fabric of the tight suit is made of 82% nylon and 18% polyester. The fabrication process is carried out with the assistance of an experienced tailor with over 20 years of expertise. After cutting the tight suit fabric according to the 2D pattern, the next step is to prepare the pressing fabric and press them together.

Preparation of Pressing Fabric. Firstly, we use an electric steam iron to bond the elastic sports fabric with the elastic hot melt adhesive film 5c together. Then, we use a lining machine to press the fixed fabrics twice at a high temperature of 170 Celsius, making the elastic sports fabric and the high elastic hot melt adhesive film 5c firmly bonded. Next, the pressing fabric is cut into strips with a fixed width of 1 cm, 1.3 cm, 1.5 cm, and 2 cm for wax pressing experiments. The comparison experiments show that the width of 1.3 cm produces better fastness in line with the experimental requirements.

Processing Note. According to the requirements of the node layout, we first conduct a bonding experiment on one sleeve. During the process, the pressing fabric will shrink when passing through the hot stamping press, causing the clothing to wrinkle and the pressed fabric tends to more easily fall off under elastic stretching. Repeated experiments show that the fabric strip needs to be pressed twice for 55 seconds at 180 Celsius in the hot stamping press to ensure the final presentation quality.

4 STATISTICS OF OUR MOTION DATASET

Fig. 3. Selected demonstration from our dataset.

We collected 248 human action files, with a total duration of 1336.9 seconds, from the Maximo website. Some motion sequences are demonstrated in Fig. 3. The types of actions include dancing, boxing, golfing, football, and other sports. We will release the full dataset to the public upon acceptance. The statistics of our motion dataset (Table 3) is as follows:

Action Type	Number of Sequences	Total Frames	Total Duration (seconds)
Dancing	61	18431	614.4
Boxing	33	1629	54.3
Golfing	16	3829	127.6
Football	13	1330	44.3
Other sports	125	14889	496.3
Total		40108	1336.9

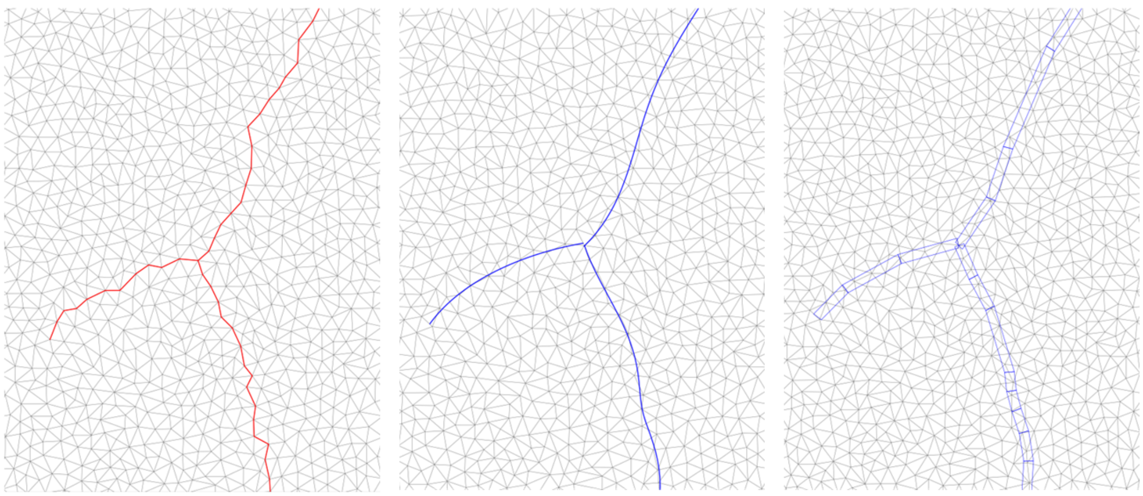
Table 3. Statistics of our motion dataset.

5 CURVE SMOOTHING

As Fig. 4 shows, The computed Steiner tree is a set of connected edges on the mesh S (a). However, its polyline nature often leads to non-smooth and sharp bending points at endpoints, hindering the wiring in real-world scenarios. Addressing this issue, we propose to iteratively smooth the computed Steiner tree with spline curves (*e.g.*, circular arcs) on the 2D pattern model (b) until its curvature κ satisfies:

$$\kappa < \frac{2}{wd}, \tag{1}$$

where wd is the width of the wire strip on the garment. This ensures that the wires do not self-overlap locally. In our experiments, we observed that this requirement can be easily satisfied in a few iterations.



(a) Raw edge (b) Curve (c) Wire strip

Fig. 4. Illustration of curve smoothing.

Algorithm 1 presents the details on the process of curve smoothing. It is worth noting that increasing the smooth factor s does not mean that the curvature can be reduced unconditionally, and in practical experiments, the maximum curvature will converge to a certain value. However, in general, the convergence value is much smaller than our set requirements ($\frac{2}{wd}$).

6 CHOICE OF MAXIMUM AND AVERAGE WEIGHT FOR DIFFERENT MOTIONS

Our experiment includes a total of 248 actions. Additional number of motion sequences can be seamlessly integrated into our layout pipeline. The combination of the weight values among different motion sequences is also a question worth exploring.

We tested two methods: 1) to compute the average value among all motion sequences and 2) select the maximum value for each mesh face. The experimental results show that the latter achieved smaller strain deformation. We believe that the average method will cause large strain deformation to occur in a small number of movements, while the maximum method can avoid this situation and ensure that each movement is equally important.

Algorithm 1 Algorithm for Curve Smoothing

```
Require: Broken lines stack L = l_1, l_2, ...l_n on 2D pattern , wiring width r
  Sup ← 100000
  while L ≠ ∅ do
      s ← 1                                          ▷ s is the smooth factor
      line ← L.pop()
      if Number of nodes in line > 4 then
          curve ← BSpline(line, s)
          while curvature > 1/r ⊓ s < Sup do
              s ← 1.1s
              curve ← BSpline(line, s)
          end while
      end if
  end while
```

7 CLOTH SIMULATION IN MARVELOUS DESIGNER

Key material properties of the tight fitting clothes are set thickness of 0.17mm and bending strength of 8. By fitting the clothing to the human body, we simulate the cloth deformation and set the quality of our simulation to 5. Additional parameters can be found in Fig. 4.

Table 4. List of parameters used in Marvelous Designer

Parameter	Value	Parameter	Value
Weft Yarn-Strength	35.0	Warp Yarn-Strength	48.0
Diagonal Tension (Right)	12.0	Diagonal Tension (Right)	12.0
Bending Strength-Weft Yarn	13.0	Bending Strength-Warp Yarn	13.0
Bending Strength-Diagonal (Right)	13.0	Bending Strength-Diagonal(Left)	13.0
Inner Damping	1.0	Density	5.0
Friction Coefficient	3.0	Thickness	0.17

8 EXPERT DESIGN PROCESS

The expert completes the design task based on the knowledge of human skeletal muscles and joint activity. The following paragraphs elaborate the detailed consideration from the expert in the design process.

Starting from the arm, the elbow is the most active part of the arm, so the route layout needs to avoid the elbow joint and be located on the outer and inner sides of the arm, which is more reasonable. Considering the high friction during the movement of the inner arm, placing the wire on the outer side of the arm is a more reasonable solution.

There are three wire layout schemes for the position of the shoulder. One is to bypass the bottom of the neck along the shoulder line and then reach the spine point. The second is to create a separate line layout through the back of the shoulder to connect the shoulder node. The third is to connect the arm to the shoulder node through a curved form, and then connect to the node on the back. Considering the forward and backward arm movements, as well as the up and down arm movements, the expert believes that the third curved connection scheme is more reasonable.

The two nodes on the back are located on the spine and do not follow a straight line because the back bends heavily on elastic fabrics, and the wires do not have elasticity. They are arranged in a curved layout, which prevents them from easily collapsing under stretching. The motion range of the waist is the largest in the entire human body, so three schemes have been proposed. The first type is to connect the nodes above and below the spine horizontally to the lateral center, and then connect them from the lateral center to the nodes on the thigh. The second type of curve first leans towards the side center and then connects to the thigh end nodes. The third method is to connect the terminal nodes of the spine and thigh in a straight line. The two terminal nodes of the legs are similar to those of the arms, using an outer routing method.

The above design principles are complex and require considerable expert knowledge and design efforts, to balance between different design plans. The design process in the mentioned tasks in our paper can only be completed by the expert in a number of days, and may involve intensive discussions with other colleagues. One expert explicitly expressed his intention to try our software: "I would strongly expect to use the software to complete the design, at least for a reference!". Therefore, an automatic solution for wire layout is in demand and preferred from the expert feedback.

9 ADDITIONAL EXPERIMENT RESULTS

9.1 One Joint

More experimental results can be seen in the Fig. 5. In single joint situation, our layout significantly reduced the relative stretching rate of the wire in all three movements, both in the maximum and average values. In the layout for the elbow joint, the maximum stretching rate of our layout was reduced by 88.6%, 94.4%, and 69.6% in three movements, respectively, and the average stretching rate was reduced by 97.4%, 99.5%, and 93.5%. This result is astonishing because the length of the layout itself is limited, and our layout successfully avoids the elbow, with almost no absolute stretching. For knee joint, the value is 94.5%, 74.7% and 90.5% for maximum stretching rate and 97.1%, 86.4% and 94.5% for average stretching rate.

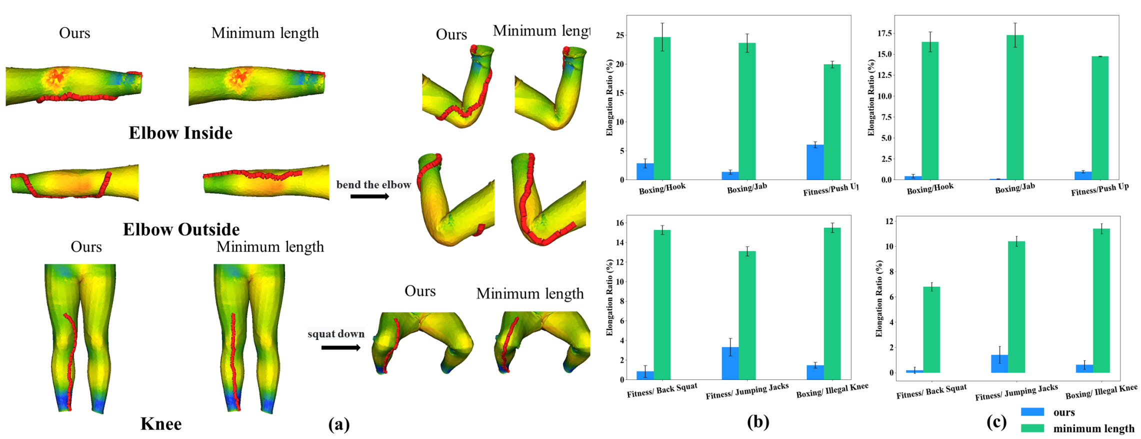


Fig. 5. The figure (a) shows the visualization results of two layouts for single joint in motion, the figure (b) shows the comparison of the maximum elongation rate of the two layouts in six movements, and the figure (c) shows the average elongation rate.

Experimental results of deformation energy also support our claims (Table 5).

Table 5. Comparison of deformation energy between our method and the baseline (minimum length).

Joint	Motion	Ours	Minimum Length
Elbow	Hook	**1191.88 ± 53.20**	2622.84 ± 248.65
	Push Up	**2006.34 ± 77.44**	3156.262 ± 80.02
Knee	Back Squat	**1018.11 ± 0.82**	1381.74 ± 2.37
	Jumping Jacks	**1176.02 ± 1.47**	1726.43 ± 14.79

9.2 Two Joints

In two joints situation (Fig. 6), the stretching performance is similar to that of a single joint, with a slight decrease in the amplitude of stretching due to an increase in the total length of the wire. In the layout for the elbow joint, the maximum stretching rate of our layout was reduced by 67.6%, 69.1%, and 47.3% in three movements, respectively, and the average stretching rate was reduced by 78.1%, 80.1%, and 81.2%. And for knee joint, the value is 66.8%, 62.5% and 58.7% for maximum stretching rate and 74.0%, 80.8% and 79.1% for average stretching rate.

10 SMART CLOTHING PRODUCT CATALOGUE

We collect the information of commercial products of smart clothing which are currently in the market (Table 6). It is common that a majority of current smart clothing products use tight suit as the underlying clothing. The tightness offers the benefit to allow the sensor to accurately monitor human state or provide feedback. The advantage is rooted from two aspects: 1) the close contact with human skin ensures that the data (for example skin-level electrical signal) is collected at a sufficiently acute level; 2) the tight fabric also maintains the electronic units at the desired location without position displacement, which could critically degrade sensor performance.

In order to link on-garment electronics, wired and wireless connections both have their pros and cons, and the decision should be cautiously weighed in the design process of every product. Wireless connection does not cause resistance to motion movement and is always the preferred solution when applicable. Wired connection is less susceptible to environmental interference than wireless connection, has higher data rate and easier power management [8]. However, as we can note in the table of product list, full body functionality, including but not limited to haptic feedaback, motion capture and electrical stimulus, often involves a considerable large number of sensors (20 or even more). In such a scenario, wireless connection encounters challenges to build a large network.

Therefore, addressing the problem of wire layout on tight suit enlightens the motivation of our work.

Table 6. Selected smart clothing products currently in the market

Product Name	Functionality	Number of Electronic Units	Tight Suit	Wired Connection
Athos [3]	Fitness Training	20	Yes	Yes
Tesla Suit [11]	Virtual Reality	46	Yes	Yes
Bhaptics [4]	Virtual Reality	40	Yes	Yes
Nadi X [6]	Fitness Training	Unknown	Yes	Unknown
Sensoria Fitness Socks [7]	Health Monitoring	3	Yes	Yes
Siren Diabetic Socks [7]	Health Monitoring	6	Yes	Yes
Ambiotex [2]	Fitness Training	Unknown	Yes	Yes
AIO smart sleeve [1]	Health Monitoring	Unknown	Yes	Yes
Hexoskin [5]	Health Monitoring	3	Yes	Yes

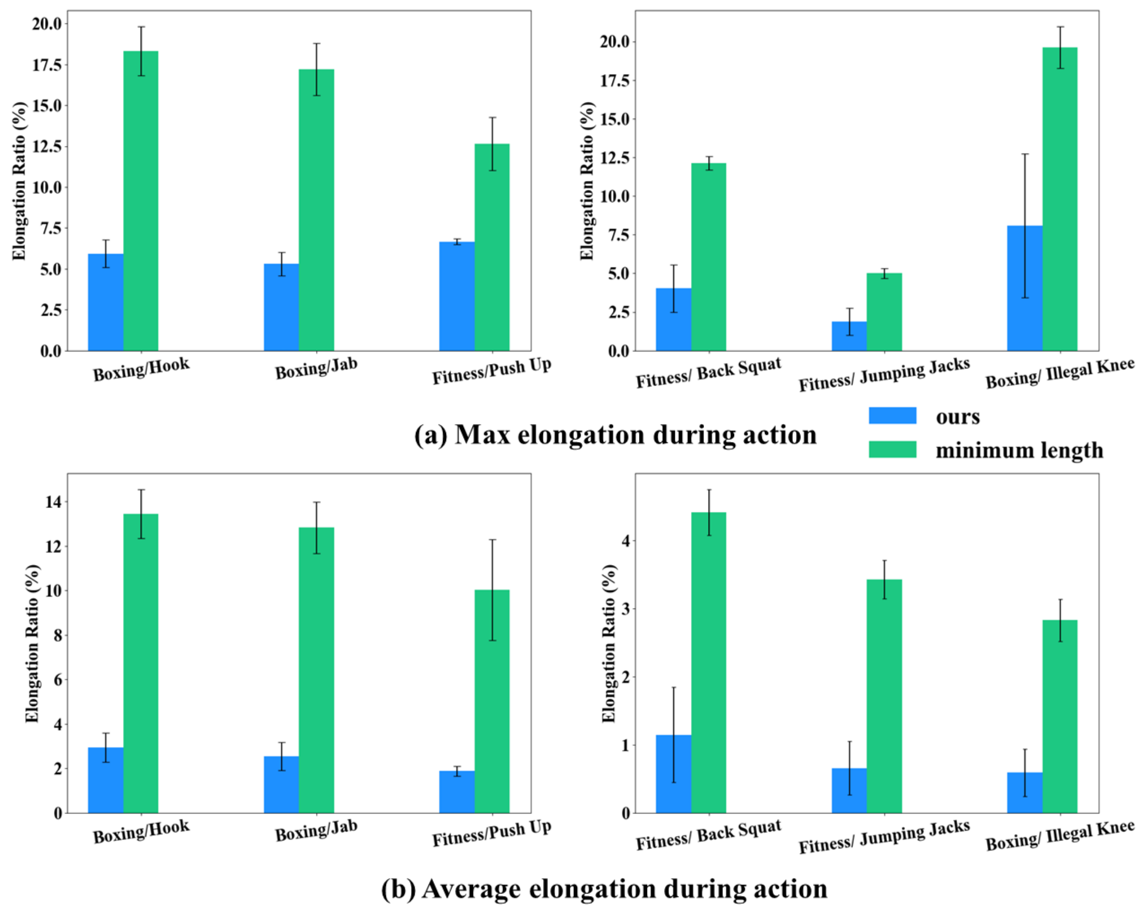


Fig. 6. The figure (a) shows the comparison of the maximum elongation rate of the two layouts for two joints in six movements, and the figure (b) shows the average elongation rate.

11 QUESTIONNAIRE & FEEDBACK

Table 7 presents a detailed result from questionnaire in our user experiment. In general, the layout designed by our method is rated with the least motion resistance and highest user experience, compared with both the minimum-length approach and the expert design.

The difference with other two layout is distinct, as participants can instantly notice the difference when switching from other layouts to ours, or vice versa. The wire designed by the minimum-length approach is broken due to large stretch on the shoulder. This should be definitely avoided in the product design, as it indicates the failure of mechanical stability. Participants vocably expressed their positive attitude towards our design. As our layout is tried on before other two, P2 said, "it feels like my normal yoga suit." A post-experiment interview led him to examine the wire layout, which he was not explicitly aware. This shows the effectiveness of our layout design approach.

	min-len		expert		ours	
Action	Resistance Level	Comfort Level	Resistance Level	Comfort Level	Resistance Level	Comfort Level
Elbow flexion	1.78±1.23	3.82±0.70	1.95±1.12	3.35±0.75	**1.25±0.72**	**4.05±0.69**
Knee bending	2.97±1.45	2.65±1.27	1.75±1.30	3.55±0.83	**1.20±0.89**	**3.95±0.59**
Back squat	3.07±1.59	2.72±1.24	2.08±1.57	3.52±1.09	**1.6±1.20**	**3.70±0.71**
Bending	2.10±1.37	3.02±0.80	2.65±1.51	2.90±0.84	**1.70±1.32**	**3.55±0.96**
Free movements	2.44±1.23	2.99±0.69	2.04±1.21	3.37±0.51	**1.51±1.07**	**3.82±0.71**

Table 7. Results from user study

12 COMMERCIAL PRODUCT OF SMART CLOTHING FOR LAYOUT REFERENCE

As smart clothing shows its potential in various applications, commercial products emerge in recent years. We here select three products:

- Tesla Suit A: a suit with inertial measurement units to monitor human motion.
- Tesla Suit B: a suit with X vibration actuators to provide haptic feedback, mostly for virtual reality applications.
- XSens: a suit with X inertial measurement units to monitor human motion.

Figure 7 shows the images of the products, highlighted with the electronics placement. As show in our experiment with expert designers, designing such a successful product requires extensive domain knowledge, including but not limited to fabric materials, garment design, human physiology and part of electronics. The complete process is trial-and-error, which is time-consuming and subject to expert knowledge and task specification. We expect that our work is a moderate attempt to resolve this challenge and provide an automatic solution to this task.

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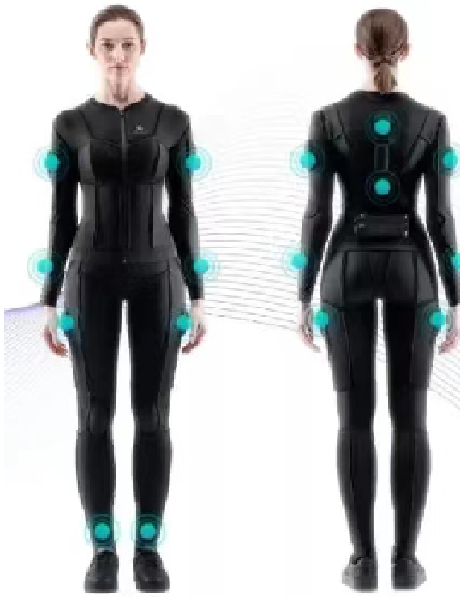
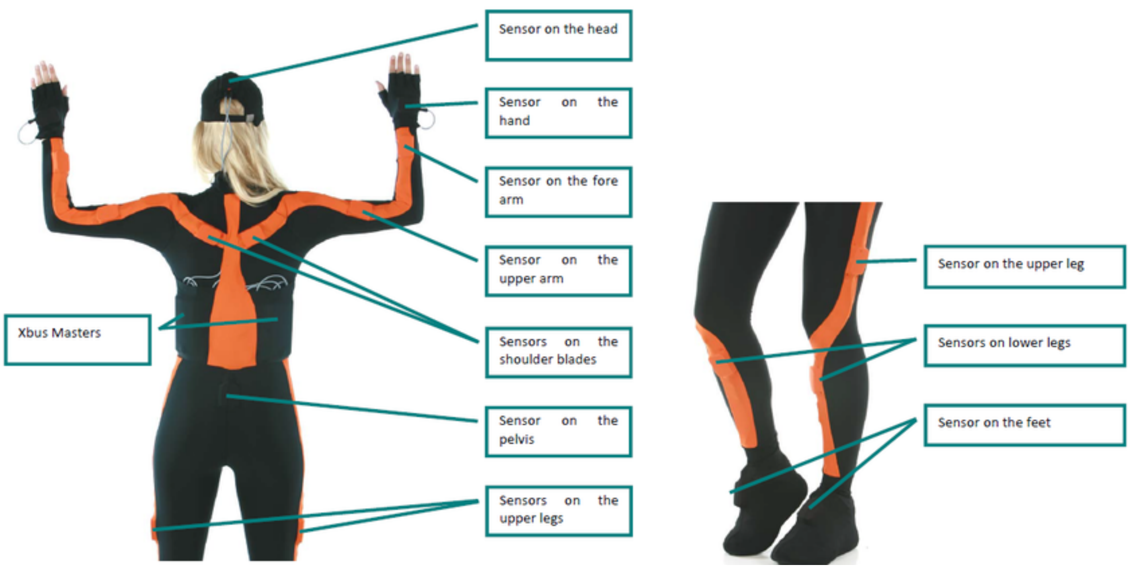


(a) Tesla Suit A

(b) Tesla Suit B



(c) Xsens motion capture suit

Fig. 7. Three commercial products of smart clothing used in our work for layout reference design.