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An Ergonomic Design Process of the Functional Clothing for Yoga Sports

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Abstract
Reports attribute many physical, psychological and mental benefits to yoga sports. However, when it comes to actual research, yoga clothing has not attracted the same level of attention. The aim of this study, which involved a questionnaire survey, clothing development and clothing performance evaluation, is to propose an ergonomic design process for the design of yoga functional clothing. Results showed that textile material was rated as the most important factor for yoga clothing. The shoulder and the waist-belly regions were considered as the most important areas for yoga clothing. The newly designed clothing prototype was observed to subject significantly lower pressure to the waist under the forward bending pose ($p<0.05$), but with significantly higher pressure on the buttocks at the posture of the deep knee bending pose ($p<0.05$). It also resulted in a lower change rate of clothing vertical displacement, especially at the shoulder and waist regions. The newly designed prototype was rated with a significantly lower tightening sensation and pulling sensation during the deep knee bending posture ($p<0.05$). Results indicate that proper design of yoga clothing structure and selection of fabric material could reduce clothing deformation, pressure on the skin and improve subjective wearing sensations.

Keywords
yoga clothing, postures, ergonomic design, clothing pressure, clothing deformation.

1. Introduction

Yoga, an ancient spiritual practice that originated in India has gained popularity both in western and eastern countries since it has been credited with many physical, psychological and mental benefits. Such benefits include improving balance, flexibility, and strength [1]. It is also helpful in managing chronic diseases, such as lower back pain [2], rheumatoid arthritis [3] and hypothyroidism (in female patients) [4], and decreasing the risk factors for cardiovascular diseases [5] and even reducing visual discomfort due to computer use [6]. Moreover, yoga has been reported to be effective for the treatment of anxiety, depression and stress disorders [7] and hence it has a positive influence on mental health and subjective well-being [8-10]. During the current COVID-19 pandemic, it has even been suggested that it can reduce anxiety and psychological distress, keep people mentally healthy whilst in social isolation, [11] prevent people from getting the virus and assist with post-recovery management [12].

Although, as already mentioned, practising yoga has many benefits, yoga clothing has not received equal research attention. Technavio [13], a leading global technology research and advisory company, reported that the yoga apparel market is expected to register a CAGR (Compound Annual Growth Rate) of over 6% during 2020-2024 due to the growing number of yoga practitioners reacting to the impact of COVID-19 pandemic. In China, although the yoga market is set to increase to 46.76 billion RMB by 2020, the yoga clothing and auxiliary equipment industries are not developed [14]. There is no special clothing for yoga practitioners and clothing for yoga is no different from other sports or training clothing [15, 16]. Park et al. [17] from Korea investigated the yoga clothing market and found that it was difficult for women over 50 years to purchase proper yoga clothing since the market mainly targeted young women. In a study carried out by Mikkonen et al. [18], the authors investigated the benefits, barriers and cues to take up yoga practice using focus groups. It was found that one-fourth of the yoga practitioners considered yoga clothing too costly which made a big barrier to yoga action. costly, which constitutes a major obstacle for those wishing to develop the yoga market.

Yoga sports usually include movement, respiration, concentration and meditation [10]. These activities are performed gently and slowly. Although the movement is slow, the body bending or twisting amplitude is large. Common poses with high flexion and bending include Stretched Spine, Cat, Camel, Lotus, and Triangle, etc., which are likely to induce musculoskeletal impingement in practitioners. Bekhradi et al. [19] based on a systematic review, reported that although the injury rate of yoga is low, nearly two-thirds of musculoskeletal injuries in yoga affect lower bodily extremities. Mikkonen et al. [18] investigated the distribution of yoga injuries and found that most were in the knee, the hamstring and the lower back. In addition, the large amplitude of body posture will induce large deformation of the clothing fabric which may cause an increase of pressure on the body via clothing [20]. Li and Wang [21] evaluated the pressure comfort of a sleeveless yoga top under various yoga postures based on 3D virtual-reality technology and found that pressure comfort could be improved by deploying yoga clothing structural optimization. Therefore, we can conclude that yoga clothing at the proper price,

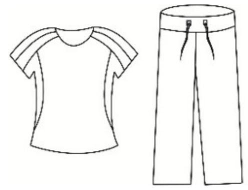
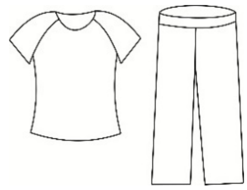
	Fiber content	Thickness (mm)	Air permeability (mm/s)	Rate of warp elongation under 1kg pulling force (%)	Style illustration
Sample A	50% cotton, 45% polyester, 5% spandex	0.42	120	4.5	
Sample B	100 % cotton	0.38	146	---	

Table 1. Details of the clothing samples

and offering a range of fabrics and designs are important for practitioners of different gender and age groups. However, research attention directed at yoga practice has mainly focused on its physical, psychological and mental effects whilst research on yoga clothing has so far been lacking.

The aim of the present study is to propose an ergonomic design process for yoga clothing and to provide knowledge and reference for functional clothing design that requires various body postures and movements. To achieve this goal, the study performed the following trials and experiments: (1) a questionnaire survey was first conducted to ascertain the clothing needs of female yoga practitioners; (2) a newly designed yoga clothing prototype was made based on the results of the questionnaire survey and normal sports clothing which is commonly used by yoga practitioners was chosen as a comparison; (3) a series of experimental tests were performed, including clothing pressure, clothing local displacement and clothing subjective sensations under various body postures; (4) based on these trials and experiments, the clothing wearing perforce of the newly designed yoga prototype and the normal sports clothing were analyzed and revealed. The study could give some hints for developing functional clothing design that is required for various bodily movements, and most of all, give some indications about how to live a yogic lifestyle during the current pandemic of COVID-19.

2. Methodology

2.1. Yoga clothing design phase

2.1.1. Questionnaire survey

A questionnaire survey was carried out among young females aged 20 to 35 who account for the largest proportion of Chinese yoga practitioners. The purpose of the survey was to ascertain the users' needs and yoga clothing preferences since clothing designs should be user-oriented, they should provide protection and comfort and also meet the end user's needs and values both materially and spiritually. [22]. Questionnaires were distributed to 60 interviewees either online or face-to-face. 55 questionnaires were returned and deemed valid.

2.1.2. Yoga clothing design

Based on the results of the questionnaire survey, a set of newly designed functional clothing for yoga sports was made (marked as Sample A). The newly designed clothing had the following features: first, it used a raglan sleeve which had two curve lines from the neck to the shoulder. Second, near the armpit, another two curve lines were designed from the shoulder to the waist. One at the front and the other at the back. Third, the waistband of the trousers was given more attention. It was made of a wide and elastic piece of fabric, which could be a single layer as a high waist or a double-layered middle waist when the fabric was rolled. This special shape and structure was designed based on the questionnaire survey of the interviewees about the yoga clothes which was presented later in the article. A knitted fabric with 50% cotton, 45% polyester and 5% spandex that was available was used to make the newly designed yoga clothes. This textile material was chosen based on three criteria: (1) comfortable to the touch; (2) stretchable to accommodate bodily movement and (3) Reasonably priced. Sportswear (marked as Sample B) which was commonly used for doing yoga and was the same size as sample A was chosen for comparison. Detailed information about the two samples is displayed in Table 1.

2.2. Subject trials phase

2.2.1. Subjects

Eight female college students were recruited to participate in the study. Their physical characteristics were as follows (Mean±SD): age=22±1years; height=165±5cm; body weight= 56±6kg and body mass index=21±2. The subjects were addressed briefly on the purpose of the study and the experimental procedure. Their right to privacy, confidentiality clauses and consent to participate in the research was elaborated on and obtained in writing.

List of yogasanas postures	Starting to final (s)	Posture maintenance (s)	Rest between repetition (s)	Total duration (s)
Standing still	5	15	30	150
High lunge pose	15	15	30	180
Deep knee bending pose	15	15	30	180
Extended triangle pose	15	15	30	180
Forward bending pose	15	15	30	180
Twisted pose	15	15	30	180
Arm raised pose	15	15	30	180
Leg press pose	15	15	30	180

Table 2. Yoga practice protocol

2.2.2. *Yoga postures*

Eight specific yoga postures were selected for the experiment The postures used were the standing still pose, high lunge, deep knee bending, extended triangle, forward bending, twisted pose, arm raised, and the leg press pose [23, 21]. Details of the yogasanas practice protocol are given in Table 2. Before the test, the subjects were instructed by the research staff to familiarize themselves with the postures. Each posture was finished slowly on a mat and maintained for 15s. Each posture was tested repeatedly three times.

2.2.3. *Experimental conditions, procedures and measurements*

The subject wear trials were carried out in a normal ambient environment with a room temperature of 22±2^{o}C and 50±5% RH. The wear trials consisted of three stages: first, the clothing pressure on the skin while doing three yoga postures was measured (stage one); second, the localized displacement of clothing during three yoga postures was measured (stage two); third, participants were asked to subjectively report the sensations they experienced while wearing the clothing doing different yoga postures. These comments were recorded (stage three).

Each subject came to the lab and put on the newly designed yoga clothing (Sample A) to finish the required tests in all three stages instructed by the research staff. Then the same tests were performed wearing normal yoga clothing (Sample B). All the tests were randomized to minimize any effects or influences that might derive from the order in which they were presented. The experimental details of the three stages were described as follows:

a. Clothing pressure measurement during three yoga postures

Clothing pressure on the skin at the centre of the back, waist and buttocks was measured by FlexiForce (Sparkfun, US) sensors. The sensors were connected to the computer and data pressure was recorded by Labview (NI, US) software. The sensors were very soft and light and can be easily placed over the skin. Medical tapes (3M, US) were used to secure the sensors. After adjusting their breaths, the subjects did three postures: standing still, deep knee bend pose, and forward bending pose (see table 2). Each of the three postures was maintained for 15 seconds, during which the pressure was measured and recorded.

b. Local clothing displacement under different yoga postures.

The local clothing displacement under three yoga postures was measured by the Optotrak certus motion capture system (NDI, Canada, Figure 1) which was frequently used to measure the displacement of the breast for bra design [24, 25] or the joint motion for the design of rehabilitation products or training [26, 27]. Six infrared-emitting diodes were placed on the subjects' left body of the shoulder, the bust, the waist (3cm vertically up from the navel), the belly, the thigh and the knee. The diodes were fixed by medical tapes. Then the subject adjusted her breaths and finished three yoga postures, including the high lunge pose, deep knee bending pose and extended triangle pose (see Table 2). The three-dimensional motion of each marker was recorded from the start (a static state) to the finish of the movement. The software recorded the data at 100 fps.

c. Subjective sensations of the clothing during different yoga postures.

The subjective sensations participants felt while wearing the clothing and doing the different yoga postures were also asked about and recorded. The subjects were asked to do the following postures: the standing still pose, deep knee bending, forward bending, twisted, arms raised, and the leg press pose (see Table 2). When these postures were performed, subjective sensations exerted by the clothing were asked about and recorded. The subjective sensations were recorded by the following scales described in table 3.

2.3. Statistical analysis

The statistical analysis was performed using SPSS 21. A one-way Repeated-measures ANOVA was employed to examine the differences in clothing local pressure, displacement and subjective sensations. Paired *t*-test was used to identify the difference. The statistical significance level was set at $p<0.05$.

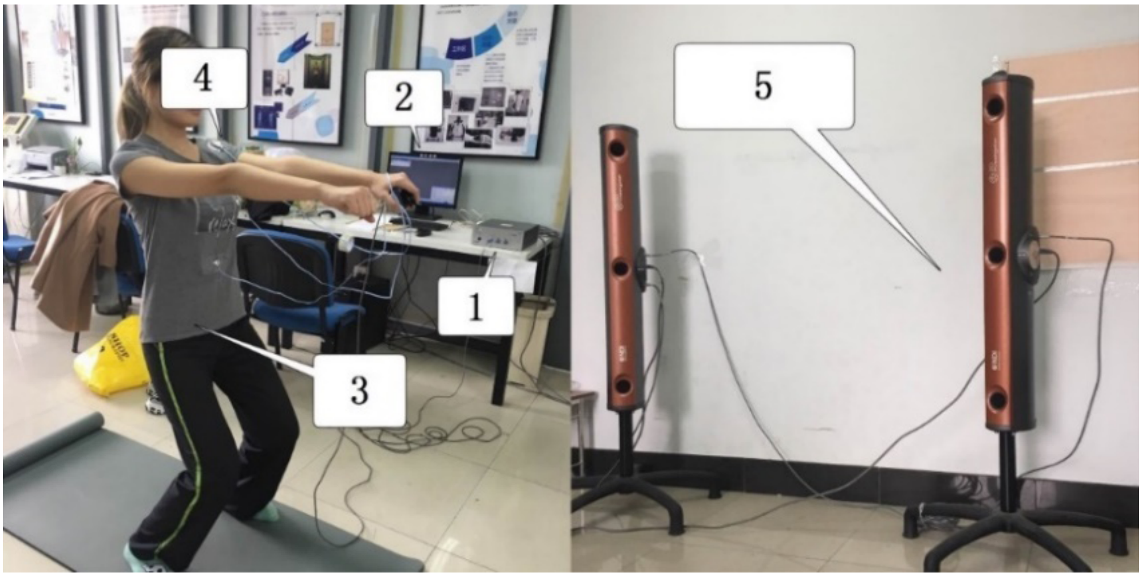


Fig. 1. Clothing displacement measurement by Optotrak certus motion capture system. 1, Sensor control unit; 2, Computer for data recording and saving; 3, Subject; 4, Infrared-emitting diode; 5, NDI sensors

Scale	Clothing fitness sensation	Clothing friction sensation	Clothing pulling sensation
5	Very tight	--	--
4	Tight	Very big friction	Very big pulling
3	Slightly tight	Big friction	Big pulling
2	Normal	Small friction	Small pulling
1	Loose	Slight friction	Slight pulling
0	Very loose (no feeling of clothing contact of pressure)	No friction	No pulling

Table 3. Rating scales of the clothing subjective sensations

3. Results

3.1. The questionnaire survey

Among the interviewees, 70% of females would like to choose professional clothing to perform yoga sports. 82% of interviewees thought that their psychological conditions could be influenced by whether wearing professional clothing or not, which indicates the importance of functional clothing for yoga sports. Figure 2 shows several important factors that influence the consumers' purchasing behaviours regarding yoga clothing. As seen from the figure, 43% of interviewees gave textile materials as the most important factor. 28% of interviewees considered the clothing structure to be the most important factor, while clothing colour, design style and detailing were the next considered factors.

Figure 3 illustrates the clothing regions of importance chosen by the interviewees when performing yoga movements and considering the involved body regions. With regards to upper body clothing, the region of the shoulder was given the most attention; this accounted for 33% of the total interviewees (Figure 3a). As for the lower body clothing, 39% of interviewees chose the waist and the belly as the most important regions for yoga exercise (Figure 3b). Hence, participants paid more attention to the shape and structural design of these body regions as shown in Table 1. The shoulder was designed with multiple pieces of curved lines from the neck to the hemline. The waist was designed with a wide, elastic waistband that could be a high waistband of one layer or rolled into a middle-height waistband of two layers.

3.2. Clothing pressure on the skin during different yoga postures

Figure 4 displays the clothing pressure of the two samples on the body skin. As can be seen from the figure, the clothing pressure of sample A in the standing posture was slightly smaller than that of sample B (Figure 4a). The two clothing samples showed significant differences in the back pressure in the standing posture ($p<0.05$). When the posture of the deep knee bending pose was performed, the clothing pressure on the buttocks was the highest among the three body positions. They were 0.76 and 0.60 kpa for samples A and sample B, respectively. The two clothing samples also showed a significant difference in clothing pressure on the buttocks in the deep knee bending pose ($p<0.05$). The reason could be that this posture required a great stretch of the hip skin and hence led to greater clothing pressure on the hip region.

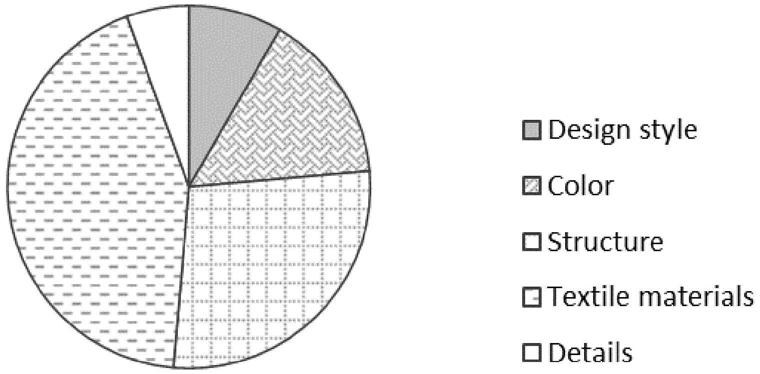


Fig. 2. Important factors of the yoga clothing chosen by the interviewees

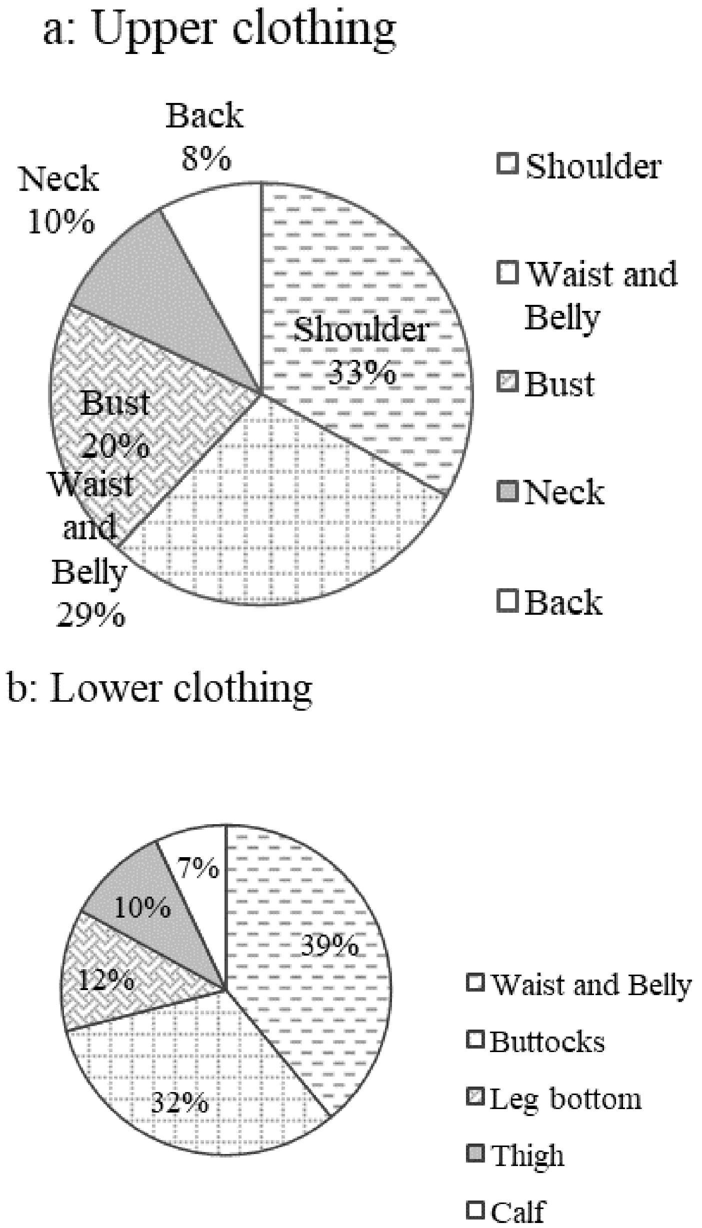


Fig. 3. Clothing regions of importance chosen by the interviewees. a) upper body clothing; b) lower body clothing

When the posture of the forward bending pose was performed, the clothing pressure on the waist was the highest among the three body positions (Figure 4c). They were 0.55 and 0.66 kpa for samples A and sample B, respectively. The clothing pressure of the two samples on the waist also showed a significant difference ($p<0.05$). This posture required great stretch of the waist skin and hence imposed greater pressure on the clothing fabric on the waist. The waistband of sample A was made of wide and elastic fabric which was more adjustable to skin stretch and hence lower pressure on the waist skin.

3.3. Clothing vertical displacement during different yoga postures

3.3.1. During the high lunge pose

Figure 5 illustrates the change rate of the clothing's vertical displacement during the high lunge pose. As can be seen from the figure, Sample B resulted in a bigger change rate of the vertical displacement in the bust, the waist, the shoulder and the knee regions, especially in the shoulder region, where the change rate was the largest. The largest change rate of the clothing vertical displacement was 2.84 mm at the shoulder region (Figure 5c). This indicates that normal sportswear had more fabric deformation in these regions, especially in the shoulder region. The newly designed clothing was designed with curved multiple pieces at the shoulder and the bust where the fabric had elastic fiber, but the normal sportswear sample was just one piece at the sleeve shoulder and bust. The clothing design of the curved multiple pieces and the elastic fabric made it more adjustable when doing the high lunge pose.

Sample A resulted in a higher change rate of vertical displacement than that of Sample B in the belly and thigh regions (Figure 5d and 5f). The largest change rate produced by Sample A in the belly region was 1.67mm. This indicates Sample A was produced with greater

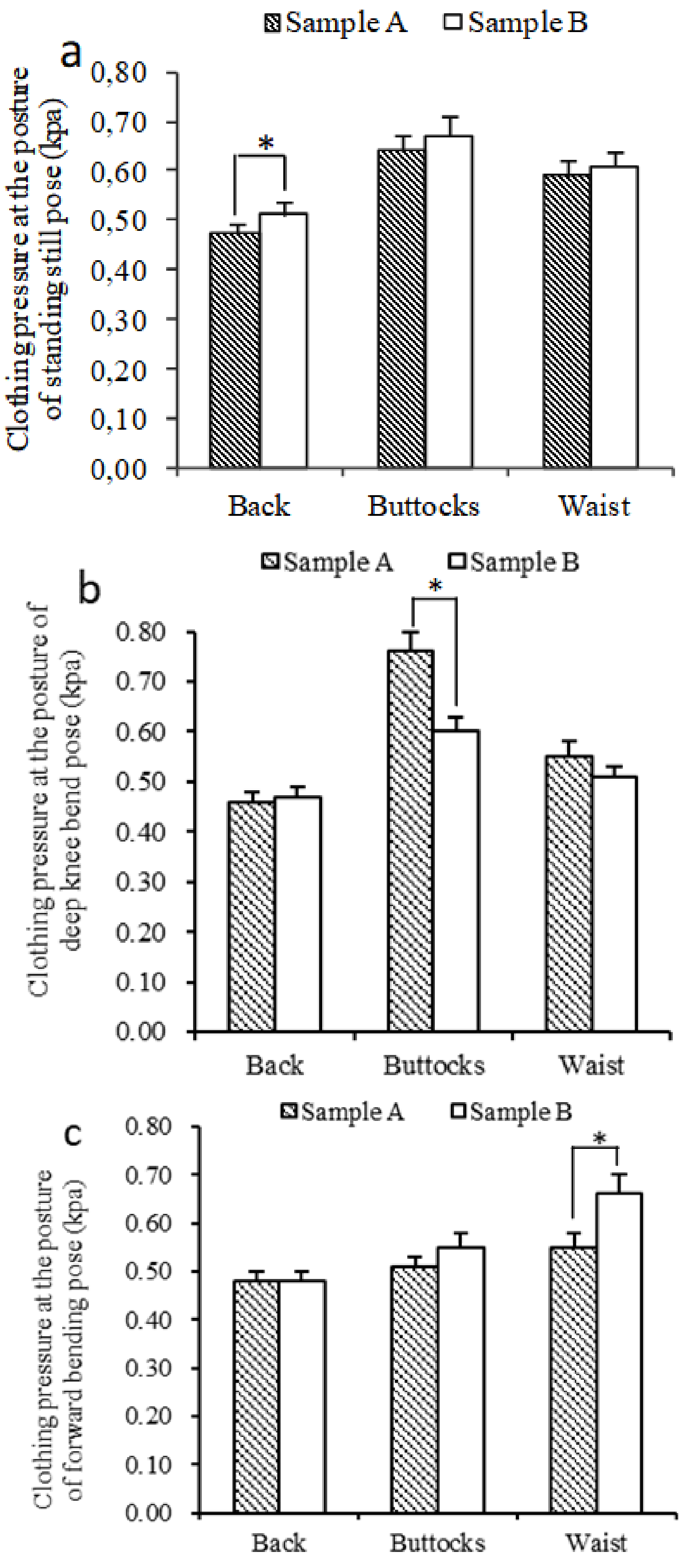


Fig. 4. Clothing pressure at different postures. "" means a significant difference at p<0.05 level.*

fabric deformation in the belly and thigh regions during this posture.

3.3.2. During the deep knee bend pose

Figure 6 shows the change rate of the clothing vertical displacement while doing the deep knee bend pose. It can be seen from the figure that except for the shoulder region, Sample B resulted in a higher change rate in the bust, waist, belly, knee and thigh regions. This indicates that Sample B had more fabric deformations in these regions. It is notable that in the waist region Sample B made the largest change rate. The largest change rate made by Sample B was 2.23mm (Figure 6b). Likewise, this indicates the newly designed clothing with the particular waistband design was more adjustable in the deep knee bend pose and hence the fabric deformation was smaller. Only in the shoulder region did Sample A result in a higher change rate of clothing vertical displacement. The largest change rate of clothing vertical displacement in the shoulder region made by Sample A was 1.60mm (Figure 6c).

3.3.3. During the extended triangle pose

Figure 7 displays the change rate of the clothing vertical displacement in the extended triangle pose. It can be seen from the figure that Sample B made a bigger change rate at the bust, the waist, and the knee regions. Conspicuously, in the waist region of Sample B resulted in a much bigger change rate of clothing vertical displacement (Figure 7b). The largest change rate was 1.85mm. This again indicates that the newly designed clothing was more adjustable to the extended triangle pose in the waist region. Sample A made a higher change rate in the shoulder, belly and thigh regions.

Most prominently, at the shoulder regions both clothing samples made a very high change rate of clothing vertical displacement. The largest change rate was 2.31mm and 2.26 mm for Sample A and Sample B, respectively. The extended

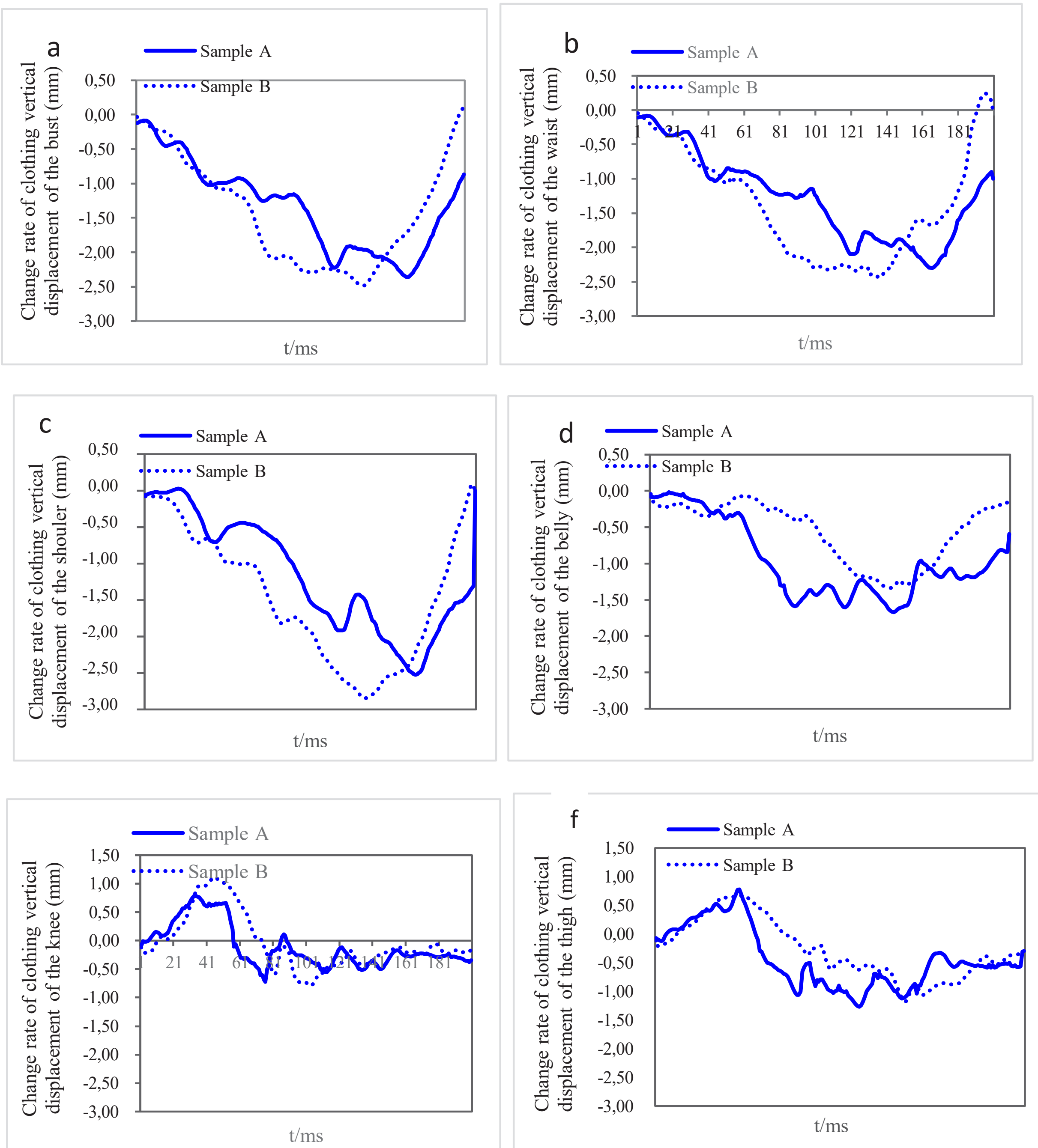


Fig. 5. Change rate of clothing vertical displacement during the posture of high lunge pose

triangle pose was performed with a very large amplitude of arm stretch and the fabric deformation of the shoulder region was hence very large. Moreover, it can be seen that the change rates of the clothing vertical displacement of the belly, the knee and the thigh were very small. The reason was that this posture was performed mainly by the upper body and hence the clothing deformation was mainly distributed to the upper clothing.

3.4. Subjective sensations of the clothing in different yoga postures

Figure 8 illustrates the clothing's subjective sensations. It can be seen from the figure that the two clothing samples showed a significant difference ($p<0.05$) in clothing fitting sensation in the deep knee bending posture. And when this posture was performed, the subjects felt that this was the tightest of the two clothes. As for clothing friction sensation, the two clothing samples showed significant differences in the deep knee bending and forward bending postures ($p<0.05$). Also when the deep knee bending pose was performed the subjects felt the biggest friction sensation. For the clothing-pulling sensation, when the deep knee bending and leg press poses were practised the two clothing samples showed significant

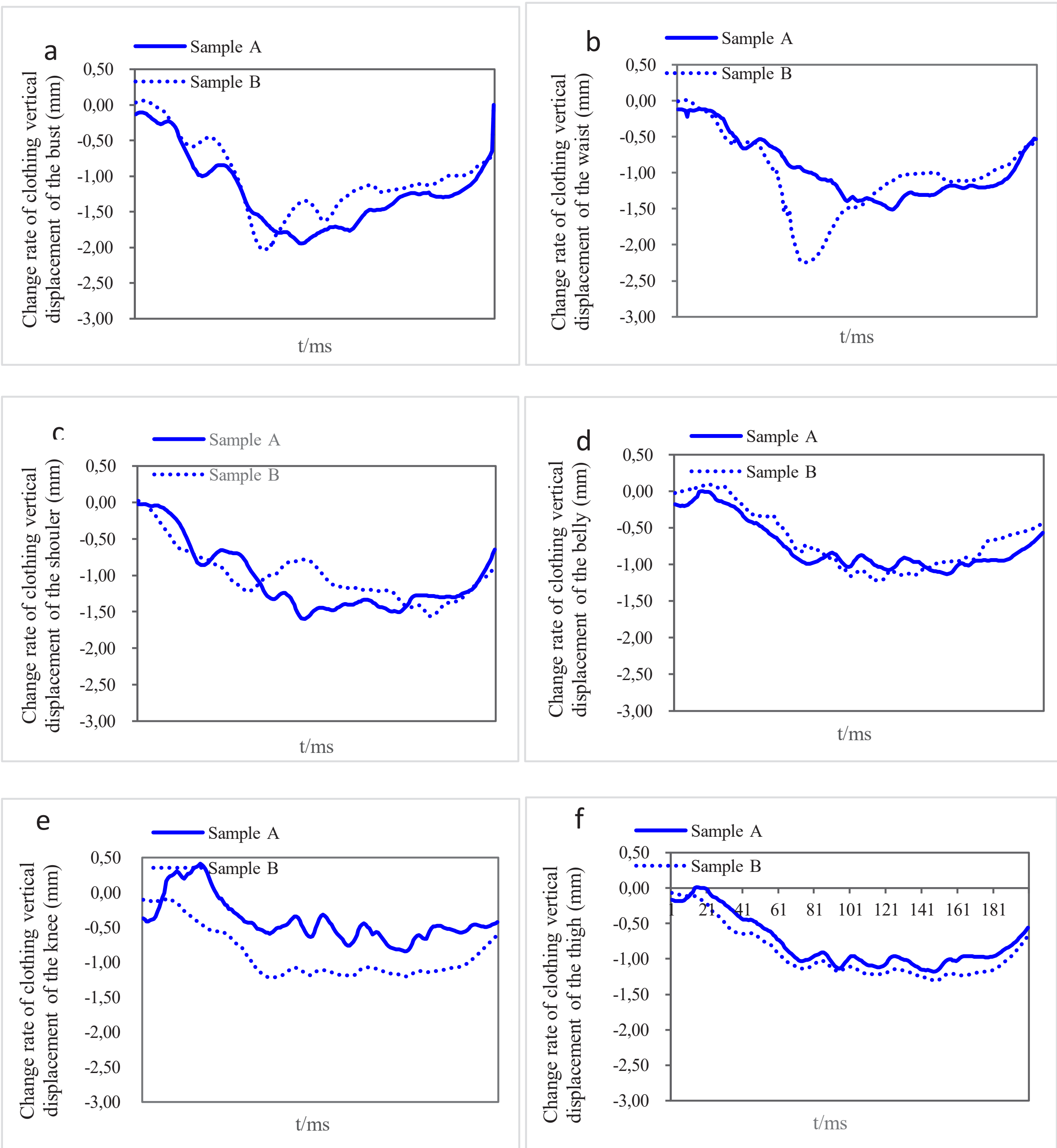


Fig. 6. Change rate of clothing vertical displacement in deep knee bend pose

differences ($p<0.05$). Evidently, it can be seen from Figure 8c that a bigger and bigger pulling sensation was recorded as arms were raised to a greater angle.

4. Discussion

In this study, newly designed functional clothes for yoga sports were developed and compared with normal sportswear by a series of tests on their ergonomic performance in different yoga postures. The newly designed yoga clothes were designed and developed based on a survey of yoga practitioners. The results indicate that the choice of textile material was considered the most important factor for yoga clothes. A similar result was found in the study of Park et al. [17] in which female yoga practitioners cited textile material as the most important buying criterion for yoga clothes. Hence, the knitted textile fabric was rated as feeling “good to the touch”, stretchy, and the newly designed yoga clothes had been reasonably priced.

The results also indicate that the shoulder, the waist and the belly were considered as the most important regions during yoga practice. The reason might be that these regions involved the most bodily

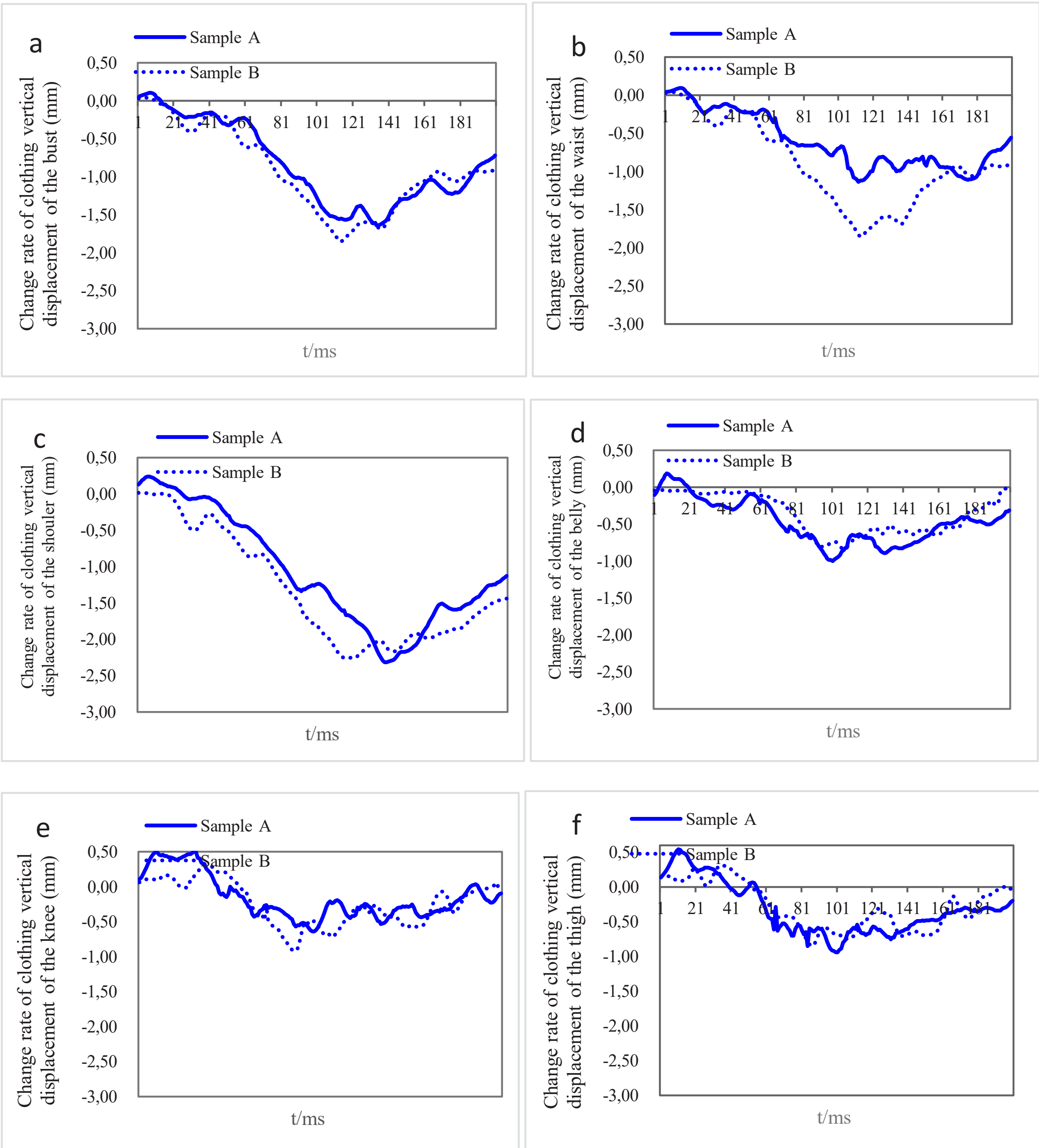


Fig. 7. Change rate of clothing vertical displacement at the posture of extended triangle pose

movements and were considered the most important ones. Hence, clothes designers pay considerably more attention to these areas of the body. According to a study by Bekhradi et al. [19], complex stretches and higher-level yoga poses would put great strain on the body, which would in turn cause injuries to the body. Therefore, the shoulder of the newly designed yoga clothes was designed in curved multiple pieces to better adjust to the yoga movements. The trousers were designed with a wide and elastic waistband with a high waist pattern of one layer or a mid-waist pattern consisting of two layers to protect the waist from flexion, twisting or rotation.

In a study by Li and Wang [21], 3D virtual-reality technology was used to evaluate the clothing pressure of a yoga top. It was found that the clothing pressure in different areas of the body varied significantly during various body postures and re-designing of the clothing top could reduce and optimize the clothing pressure. This was also indicated in the present study, which shows that the structure and fabric of the newly designed yoga clothing reduced

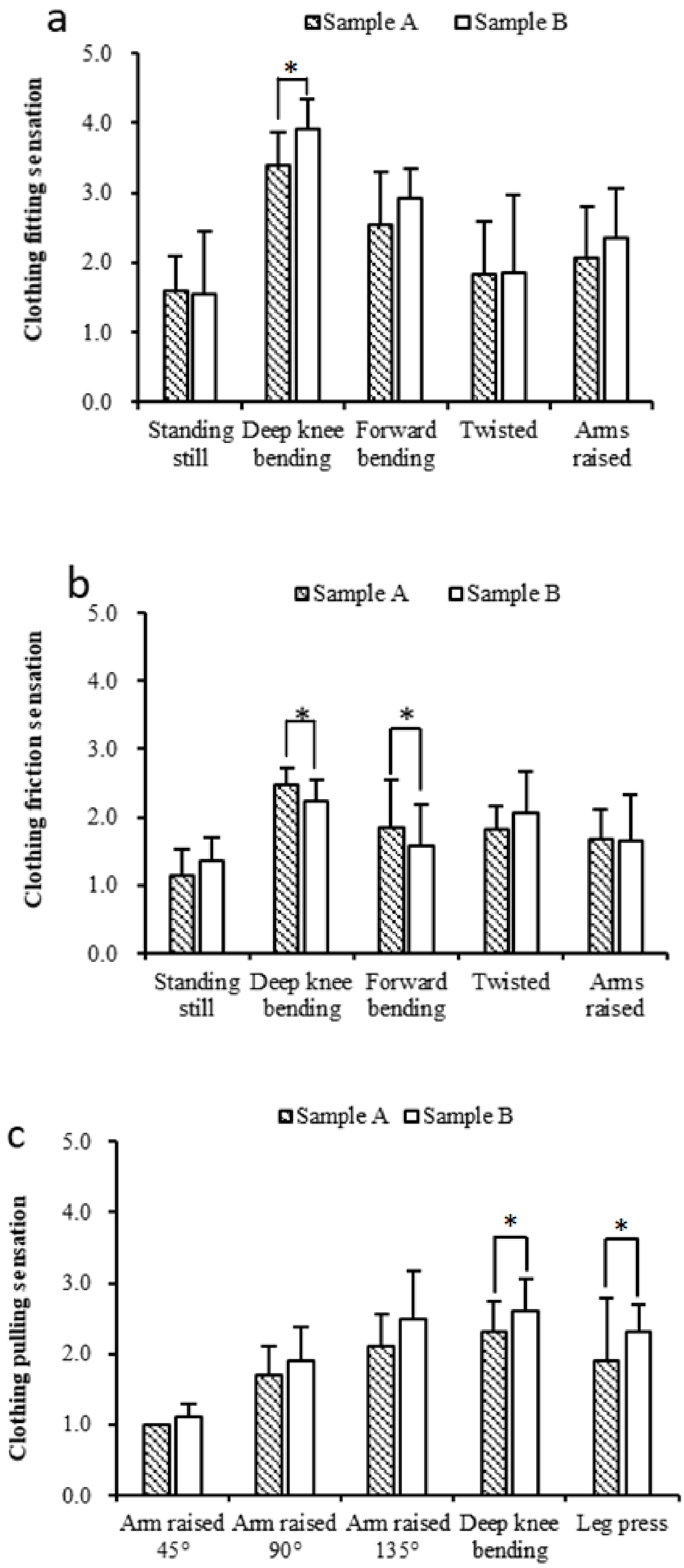


Fig. 8. Ratings of clothing subjective sensation. "" means a significant difference at p<0.05 level.*

clothing pressure in some parts of the back, buttocks and waist. Besides, the results of the subjective ratings showed that the bigger range of the body motion, the higher friction and pulling sensation imposed by the clothing. The newly designed yoga clothing reduced the pulling sensation compared with that of normal sportswear in the various yoga postures. This indicates that the subjective wearing sensations were improved by the clothing's structural design and fabric selection.

Clothing vertical displacements in six localized regions in three yoga postures were also examined and compared. The results showed that a bigger amplitude of body postures causes more clothing displacement, i.e., more fabric deformation. In the bust and waist areas, the newly designed yoga clothes displaced clothes less. This indicated that the newly designed yoga clothes with their stretchable fabric and special structure were more adjustable when doing the three yoga movements. The normal sportswear was made of pure cotton without spandex and was made with a conventional structure, hence, it caused more fabric deformation in the three yoga postures.

5. Limitations and conclusions

This work has some limitations. First of all, only young females aged 20 to 35 were surveyed. Since yoga practice is popular and fashionable mainly in bigger cities with females who work full time, and practise after work for postnatal recovery, yoga practitioners of other age groups and gender were not included. Secondly, only one yoga clothing prototype was designed as a case study due to limitations on project time, funds etc. Thirdly, when measurements of clothing local displacements were made, only the vertical displacement was analyzed due to the large amount of data gathered and the focus of the study. These limitations should be completed and included in the study in the near future.

The study proposed an ergonomic design process for functional clothing for yoga sports which involves various body poses and movements. Results indicate that textile material was considered to be the most important factor for yoga clothing. The shoulder and waist-belly regions were considered the most important areas as they are involved in most bodily movements. Clothing pressure on the body skin in the three local regions varied. The change rate of the clothing vertical displacement in different localized regions also varied. Appropriate design of the clothing structure and the selection of the fabric materials could reduce clothing pressure on the skin and as well as reduce clothing vertical deformation. Clothing fitting and pulling sensations were significantly different when the functional garment was made with different structures and fabrics. Other indoor sports such as callisthenics, gymnastics and aerobics, etc. also involve various body poses and movements and hence, the presented design process could be used as a reference for designing functional clothing for these indoor sports also.

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