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Next Generation PU Foams for Mattresses benign to Human Body

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The next generation PU form of High Resilience (HR) and Viscoelastic (VE) foam for mattresses was developed, improving hysteresis loss, air permeability under compression and temperature sensitivity. We utilized ergonomics from the initial development stage to evaluate the comfort of the mattress with body pressure distribution performance and the ease of rollover in the bed. Moreover, we evaluated sensory inspection and analyzed using the next generation foam, VE foam and HR foam under actual sleeping conditions. In this study, we clarified the correlation of the results between the physical property values of the flexible polyurethane foam and the ergonomics evaluation.

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1. Introduction

In today's modern society, in which people are over scheduled and more stressed than ever, time for restful sleep is being sacrificed. The burden to provide a better night sleep is being placed on mattress manufacturers. Developing mattresses which reduce pressure points on the human body will correlate with sleeping quality. From this viewpoint, better mattresses today are required to decrease the load on the waist and the back. Specifically, the provision of the mattress that can maintain natural body posture and rollover ease is our market goal. It is known that flexible polyurethane foams consisting of mainly high resilience (HR) foams and viscoelastic (VE) foams have been used in mattresses. Production volumes of both HR foams and VE foams have increased considerably from 2004 to 2007 [1]. The technology concerning HR foams using TDI (toluene diisocyanate) and MDI (diphenylmethane diisocyanate) has been reported since the 1990's [2][3]. As HR foams have high strength at the deflection, the conventional flexible polyurethane foams used in mattresses have been made using a dual layer or profile cut surface to improve human body pressure distribution [4]. On the other hand, the technology concerning VE foams has been reported since 1998 [5][6]. VE foams decentralize the body load and thus provide better body pressure distribution than HR foams. However, VE foams have problems with temperature sensitivity and individuals sinking into the foam while sleeping. These disadvantages result in a change in significant foam hardness, reduction in the ease of rolling over while sleeping, and increase in the frequency of waking up sweatily rather than refreshed after a good night sleep.

AGC has developed a new generation flexible polyurethane foam for the mattress which harmonizes the advantages of both HR foams and VE foams. The new flexible polyurethane foam features excellent body pressure distribution, low temperature sensitivity and minimal hysteresis loss. The frequency of becoming sweaty or perspired while sleeping is significantly decreased because of the excellent airflow through the foam even while being compressed. The sensory inspection of the flexible polyurethane foam has been mainly evaluated at the sense of touch [7][8]. We introduced ergonomics from the initial development stage to clarify the relationship between physical property data of the next generation foam and human comfort while sleeping[9]. This analysis between the ergonomics data and polyurethane foam properties was useful for the improvement of mattress performance. As a result, we succeeded in the development of the mattress that offered the comfort to the cusumer by doing the above mentionded examination.

2. Experimental

2.1 Foaming Procedure (Laboratory Foaming Test)

Foam samples were prepared by hand mixing with polyol and isocyanate at the temperature of 23℃. Free rise foams were produced in a corrugated cardboard box, 600 × 600 × 400 mm in size. Physical properties of the foams were measured according to JIS K6400 (1997). Target foam densities were 34kg/m³ to 60kg/m³. Physical properties of each target foam density are listed in **Table 1.**

Table1. Physical properties of Next Generation Foams produced by hand mixing foaming.

Target Density	kg/m^3	60	48	42	34
Density	kg/m^3	62.1	49.1	42.5	33.7
25%ILD(Indentation Load Deflection)	$N/314cm^2$	86	81	80	89
65%ILD(Indentation Load Deflection)	$N/314cm^2$	198	180	173	194
Sag-Factor		2.30	2.20	2.16	2.18
Air Flow	L/min	23	45	28	42
Impact resilience	%	9	8	12	10
Hysteresis loss	%	28.2	37.5	46.1	50.3
Compression set 50%	%	2.2	2.6	2.2	3.2
Compression set 90%	%	4.2	5.2	4.8	5.3

2.2 Physical Properties

Physical properties of the foams and the air permeability were measured according to JIS K6400 (1997) and ASTM D 3574-08, respectively. The glass transition temperature (Tg) was obtained by the dynamic viscoelasticity measurement in accordance with JIS K7244 at a 10Hz frequency using a Seiko Instruments DMS 6100. The temperature was raised at a rate of 3℃ / min under a nitrogen atmosphere.

3. Results and Discussion

3.1 Mattress Samples

The foam of ca. 60 kg/m³ in density as a next generation foam shown in **Table 1** was produced with a conventional slab stock line. In order to compare and evaluate characteristics of the next generation foam, we chose a commercially available HR foam mattress and VE foam mattress consisted of single polyurethane foams without dual layer and profile cutting. Measurement results of these three samples are listed in **Table 2**. Although the hardness of the next generation foam is between that of VE foam and HR foam, it has unique characteristics of low hysteresis loss and impact resilience. Furthermore, the air permeability, which is an issue with VE foam, was improved.

3.2 Relationship Between Physical Properties of Polyurethane and Mattress Comfort

3.2.1 Body Pressure Distribution Performance

It was assumed that the excellent body pressure distribution of the foam was achieved because the foam cells were uniformly compressed during pressurizing. In order to clarify this assumption, we examined visualization experiments as follows. After drawing a 1 × 1 cm lattice pattern on the side of 70 mm thick foam, it was compressed to be 25% and 50% of the thickness using a 314cm² disc plate as shown in **Fig.1**. The differences in each foam compression are visualized by the lattice pattern deformation. It is clear that cells of the next generation foam were compressed uniformly. On the other hand, both HR foam and VE foam were compressed heterogeneously because of partially concentrated stress. According to these results, we suppose that the next generation foam demonstrates better body pressure distribution performance compared with HR foam and VE foam

Table2. Physical properties of flexible polyurethane foam for mattresses.

Property	Unit	Next Generation Foam	VE Foam	HR Foam
Density	kg/m³	57.9	87.1	27.4
25%ILD (Indentation Load Deflection)	N/314cm²	80	55	160
65%ILD (Indentation Load Deflection)	N/314cm²	178	133	278
Sag-Factor		2.21	2.43	1.74
Air Flow	L/min	60	1	120
Impact resilience	%	12	2	38
Hysteresis loss	%	29.2	56.0	41.2
Compression set 50%	%	2.0	1.8	2.3
Compression set 90%	%	7.5	18.3	6.8

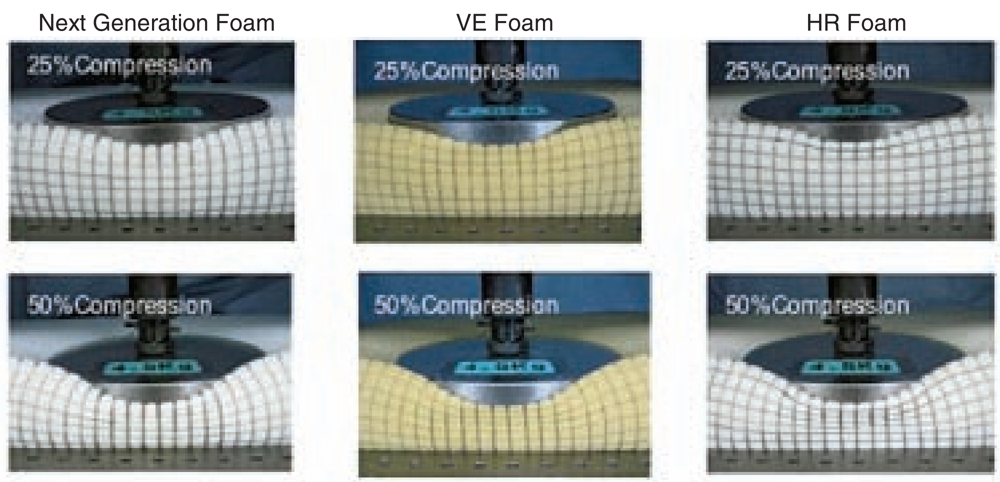


Fig.1 Comparison with compression behavior for flexible PU foams.

3.2.2 Air Permeability under Compressions

The human body emits 200 to 300 ml（up to 1L）of body moisture each night. One third is emitted through breathing. The remaining two thirds are transmitted through the body surface and have to be absorbed by mattress（25%）, sheets, blankets and pillow（together 75%）. Humidity regulation depends mainly on the top layer structure（80%）of the mattress. The core（20%）of the mattress is relatively unimportant, as far as it is able to act as a buffer to transport the captured moisture between the top layer and the environment [10].

The next generation foam can decrease the perspired feeling while maintaining the excellent body pressure distribution. It was estimated that the uniform cell compression did not disturb air flow. In order to confirm this phenomenon, the air permeability of the compressed foams was measured. The foam samples of 51 × 51 × 25 mm size were compressed into 25%, 50%, and 75% of its original foam thickness with a device that did not disturb the flow of air, and its air permeability was measured. Measurement results of the next generation foam and VE foam are shown in **Fig.2**. These results indicate that the next generation foam has high air permeability even under compression conditions, and thus this accounts for the decreased perspired feeling compared to the other foam mattresses.

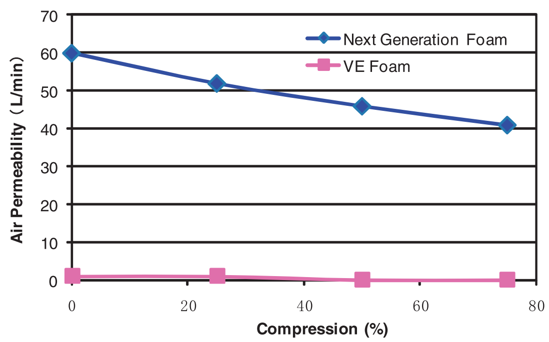


Fig.2 Comparison with air permeability at compressions.

3.2.3 Temperature Sensitivity

The next generation foam has improved the temperature dependence issue associated with VE foam. In order to confirm this characteristic, we measured glass transition temperature（Tg）of the next generation foam（−10.4℃）and VE foam（11.1℃）by DMS（dynamic mechanical spectroscopy）. Furthermore, foam hardness of the next generation foam and VE foam under various temperatures at 0, 10, 20, and 30℃ was measured with F-type hardness tester, shown in **Fig.3**. The foam hardness of each foams at 30℃ is equal. On the other hand, the VE foam hardness significantly increased lower temperatures, exhibiting that the next generation foam hardness was 35,while VE foam hardness was 91 at 0℃. These measurement results obtained using both Tg and the F type hardness tester show that the next generation foam has much better temperature sensitivity performance than VE foam even at room temperature.

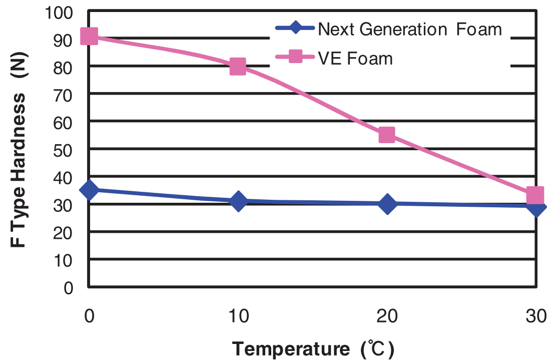
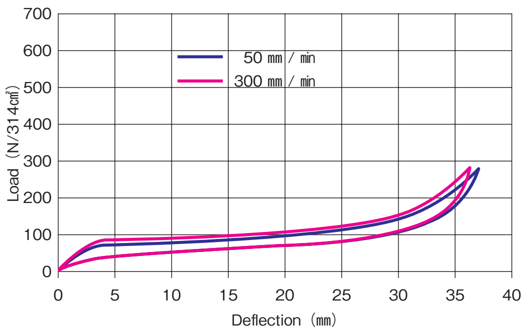


Fig.3 Comparison with temperature sensitivity.

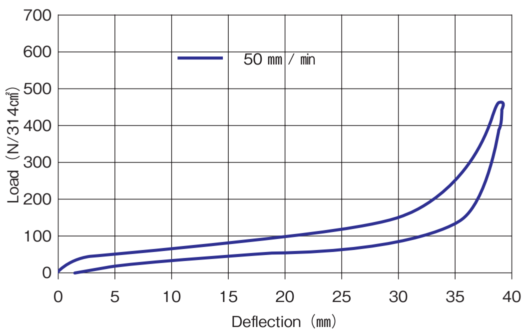
3.2.4 Rollover Ease

Frequent posture changes during sleep require sufficient mobility of mattress. When a mattress is too soft and nearly surrounds the human body, it requires a lot of energy or even becomes impossible to rollover. [10]. It is usually easy to roll over on polyurethane mattresses because polyurethane foam flows with body mobility. Foam following mobility is represented by hysteresis loss of the foam. A polyurethane foam with a low hysteresis loss means that when people rolls over on the mattress, the polyurethane foam flexes with the human body motion. Hysteresis loss of the three foams ; the next generation foam, HR foam and VE foam of 50mm thickness respectively were measured at a push speed of 50mm/min and 300mm/min to 75% of each foam thicknesses from their original ones. The results are shown in **Fig.4**, **5** and **6**. The hysteresis loss of the next generation foam was the lowest of the three foams tested. VE foam hysteresis loss could not be measured at 300mm/min speed, because the recovery time of VE foam was extremely slow（**Fig.5**）. This result suggests that VE foam is difficult for the human body to roll over on the mattress. The next generation foam exhibits the greatest rollover ease of the 3 foams evaluated.



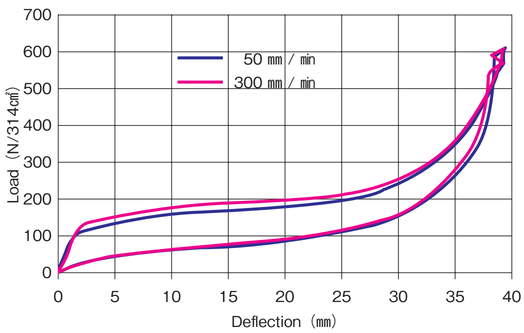
Push Speed :	Hysteresis Loss (%)
50 mm / min	25.9
300 mm / min	34.0

Fig.4 Hysteresis loss of Next Generation Foam.



Push Speed :	Hysteresis Loss (%)
50 mm / min	46.3
300 mm / min	measurement impossible

Fig.5 Hysteresis loss of VE Foam.



Push Speed :	Hysteresis Loss (%)
50 mm / min	40.9
300 mm / min	41.6

Fig.6 Hysteresis loss of HR Foam.

3.2.5 Quantifications of Bottoming Out

Since the hardness change of VE foam is very sensitive to temperature and burden, the sinking into the VE foam increases in accordance with body weight and circumstance temperature. It is well known that VE foam tends to bottoming out. When bottoming attack has happened, sleeping posture in the mattress worsens. In this study, we evaluated quantification modeling of bottoming out. The hip type model defined in Japanese Automotive Standard (JASO B407) was used instead of human body (**Fig.7**) . The creep strain examination was measured for ten minutes by using this model (**Fig.8**) . A constant load was decided as 45% of his weight, supposing an adult Asian man lying on the bed and calculated as follows : 68kgf (weight) × 9.8N × 0.45 = 300N [11]. 300N of the load was kept for 10 minutes by using above mentioned hip model under the condition of 23℃ and relative humidity 50% with the next generation foam and commercial available VE foam at the sample size of 500mm × 500mm × 70mm (thickness) . Test equipment used was SHIMADZU CORPORATION MODEL AUTOGRAPH AG-20kNIS. Pressure was measured using an Xsensor® X2GSM-8. Since this mapping sensor can indicate pressure situation directly, it is easy to detect bottoming out.

Fig.7 The hip type model based on JASO B407.

Fig.8 Creep strain examination using hip model.

Measurement results of the creep strain are shown in **Fig.9**. The red color indicates a pressure greater than 50mmHg. The average pressure value of VE foam rose up by 8mmHg in 10 minutes. In contrast, the next generation foam indicated constant average pressure for same period. Whereas VE foam might have a tendency to bottom at room temperature from the above observation, the next generation foam would provides comfortable sleeping posture without bottoming out.

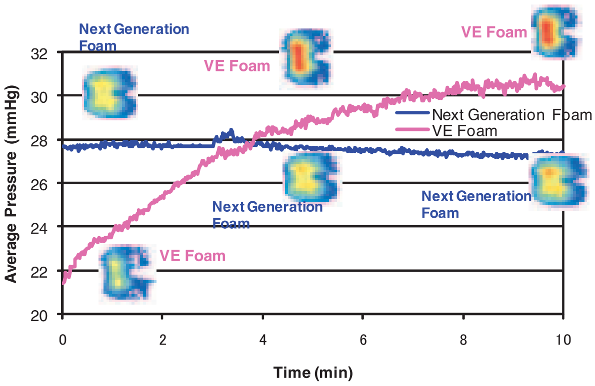


Fig.9 Comparison of bottoming out between Next Generation Foam and VE Foam.

3.2.6 Quantifications of Comfort Ability for the Mattresses Based on Human Factor of Ergonomics

It is clear that the next generation foam exhibits such distinguished characteristics as excellent body pressure distribution and much easier rollover ability. In order to clarify the relationship between the next generation foam and comfort for actual human body, we evaluated the characteristics of the mattress in the view point of ergonomics.

3.2.7 Body Pressure Distribution Properties

When sleeping on too firm surface, body weight would not be distributed homogeneously, and the contact area would be reduced, resulting in increasing pressure and shear forces (parallel to mattress surface) on the skin and the underlying soft tissues (e.g., blood vessels). Blood supply would be reduced or even stopped due to the deformation of these tissues. Normal capillary arteriolar pressure should vary between 25 and 35 mmHg. Pressure in the venules should be approximateiy 12 mmHg, while critical pressure is considered to be 30 mmHg. The combined effect of loading time and strong intensity at a same area may result in bedsores, especially when a patient cannot move because of injuries, for example. [10]. Therefore, even for a healthy person, it is desirable to distribute his or her body weight.

Distribution analysis is relatively easy to be accomplished by pressure interface measurements, which can be performed by mapping system with blanket containing pressure sensors matrix. The system, Xsensor® X2GSM-8, was placed between the mattress surface and the human body. The dimensions of each mattress were as follows ; the next generation foam mattress : 940 (W) × 1900 (L) × 100mm (H), commercial VE mattress : 940 (W) × 1950 (L) × 70mm (H) and commercial HR mattress: 970 (W) × 1980 (L) × 110mm (H). Room temperature was controlled at 23℃ and the body pressure was measured after 30 seconds. The distribution properties and the statistics data were indicated as average pressure, maximum pressure and contact area. As for the average pressure and the maximum pressure, lower values are desirable. There is an inverse correlation that when the contact area becomes smaller, the maximum pressure is higher. In general, the contact area should not be too small. When sleeping on too firm surface, body weight will not be distributed homogeneously, resulting in increasing pressure and shear forces, and giving rise to the symptoms mentioned earlier.

Table3. Physical attributes of subjects.

Subjects	Gender	Height(cm)	Weight(kg)	BMI(kg/m^2)
A	Male	182	85	25.7
B	Male	170	70	24.2
C	Female	156	48	20.0

On the other hand, too large a contact area, designed in order to prevent blood circulation disorders, causes the person to sink deeply into the mattress and limit body mobility [10]. Subjects of anthropometric data are shown in **Table 3**.

Measurement Methods	Units	Next Generation Foam Mattress	VE Foam Mattress	HR Foam Mattress
Body Pressure Distribution using X-Sensor				
Average Pressure	mmHg	26.0	28.9	37.0
Max Pressure	mmHg	72.7	72.1	101.5
Contact Area	cm^2	4,050	3,629	3,100

Fig.10　Body pressure distribution mapping of subject A.

Measurement Methods	Units	Next Generation Foam Mattress	VE Foam Mattress	HR Foam Mattress
Body Pressure Distribution using X-Sensor				
Average Pressure	mmHg	20.8	27.3	32.0
Max Pressure	mmHg	64.4	84.1	72.4
Contact Area	cm^2	3,724	2,900	2,567

Fig.11　Body pressure distribution mapping of subject B.

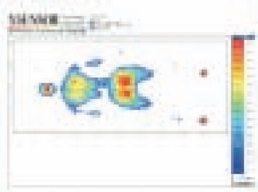
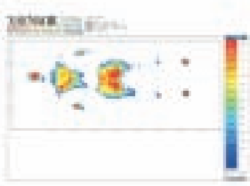
Measurement Methods	Units	Next Generation Foam Mattress	VE Foam Mattress	HR Foam Mattress
Body Pressure Distribution using X-Sensor				
Average Pressure	mmHg	22.9	28.5	34.0
Max Pressure	mmHg	53.5	59.6	62.4
Contact Area	cm^2	2,816	2,192	1,577

Fig.12　Body pressure distribution mapping of subject C.

Measurement results of each body pressure data and mapping pictures are indicated in **Fig.10, 11** and **12**. According to the pictures, the next generation foam had less red areas at the hip area in comparison to VE foam and HR foam. Moreover, the next generation foam had lower average and maximum pressure values than VE foam and HR foam had the highest contact area of the three mattresses. Therefore, the next generation foam demonstrated to have the best performance. We consider that the excellent body pressure distribution achieved here stems from the uniform foam cells compression when the foam is pressurized.

Next, we evaluated the relationship between three mattresses and BMI (weight/ height^2) factor, including 6 adult males and 40 adult females. Body pressure distribution was measured using the method described above at 25.1℃, and 59% of relative hummidity. The correlations of BMI values with average pressure, maximum pressure and contact area are shown in **Fig.13**, **14** and **15**, respectively. The average pressures of the next generation foam were low in almost all the BMI values (**Fig.13**). In the case of maximum pressure values (**Fig.14**), relatively lower tendency is recognaized for the next generation foam. Moreover, the next generation foam indicated higher contact area than any other foams (**Fig.15**). From these results, we confirmed again that the next generation foam had an excellent body pressure distribution performance.

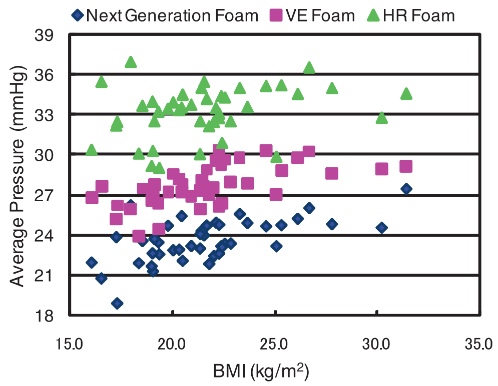


Fig.13 Relationship between BMI and average pressure.

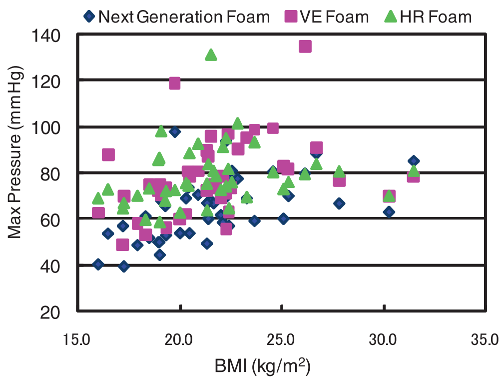


Fig.14 Relationship between BMI and max pressure.

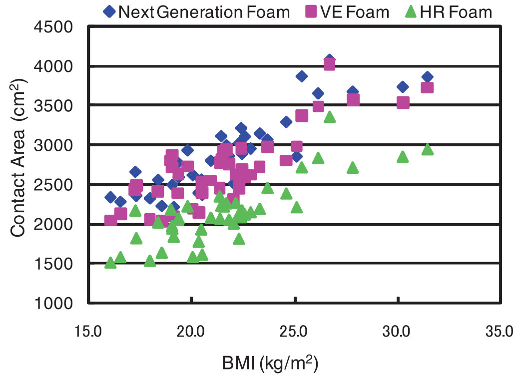


Fig.15 Relationship between BMI and contact area.

3.2.8 Rollover Ease

Posture changes during sleeping are necessary to avoid a pressure overloading to soft tissues and to prevent muscle stiffness. The regular position shift number is about 20 a night. On some kinds of waterbed, pressure distributors, or too soft mattresses, the pelvic girdle would sink deep and the person roll back into the cavity when trying to change his or her posture [10].

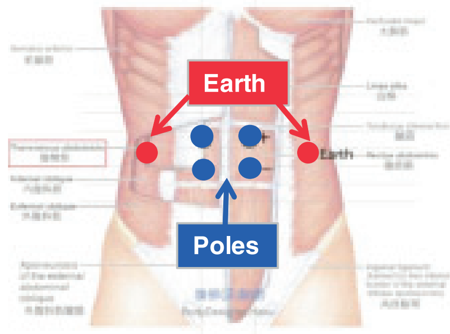


Fig.16 Electrodes attached to the locations.

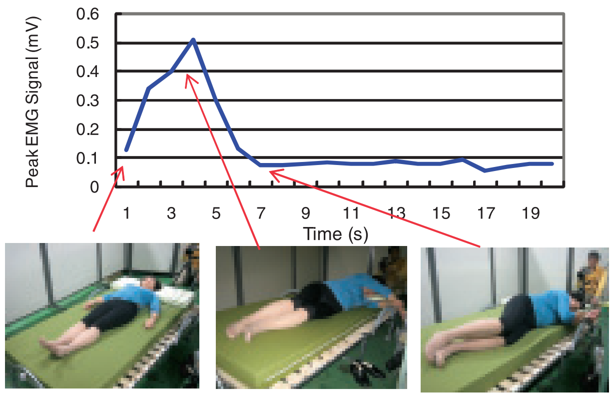


Fig.17 Rollover method and the electrodes.

Therefore, the easy rollover mattress must have a low load to muscles. The ease of rollover was evaluated with EMGs (electromyogram) and the muscle group active in rollover actions was chosen to be identified from right and left rectus abdominises. The subjects had electrodes attached to the locations indicated in **Fig.16**. The rollover method and the electrode values are indicated in **Fig.17**. The instrument used was a biologic information recorder with a bio-amplifier, PowerLab / 8SP, Model ML785, by ADInstruments, with disposable ECG electrodes. The physical attributes of the subjects were given in **Table 4**. Ten rounds of rollover were performed for each sample mattress with a 3-minute break in between. The loading dose indicated was integrated with the electromyogram of **Fig.17**, and evaluated 10 times. As shown in **Fig.18**, the next generation foam was the mattress with the least load to the muscles. Therefore, it is apparent that the next generation foam provides better rollover ease performance than VE or HR foams.

Table4. Physical attributes of subjects.

Subjects	Gender	Height(cm)	Weight(kg)	BMI(kg/m^2)
A	Female	159	59	23.3
B	Male	173	66	22.0

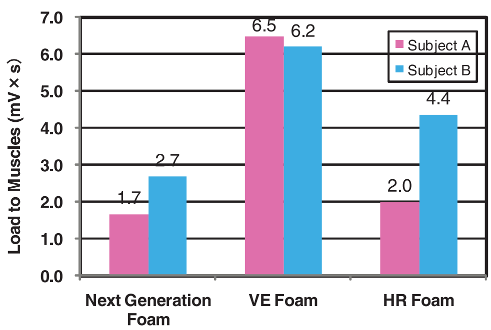


Fig.18 The load to muscles of subjects at rollover.

3.2.9 Sensory Analysis of Sleeping

The usage of the mattress is greatly different depending on individuals and families. The sensory evaluation study using three sample mattresses was carried out with 6 individuals to sleep in their own room for 5 nights. An interval of 2 nights was set between the 5-night-test periods before sleeping back in their own bed.The sensory evaluation was executed by having individuals answer survey questions each morning when they got up. An ergonomics specialist made the survey questionnaire, which included items such as: Felt Warm, Felt Humid, Felt Cold, Low Back Supported from Beneath, Easy to Rollover, and Body Pressure felt Dispersed. **Fig.19**, **20** and **21** show the result of how many people felt the features each night.

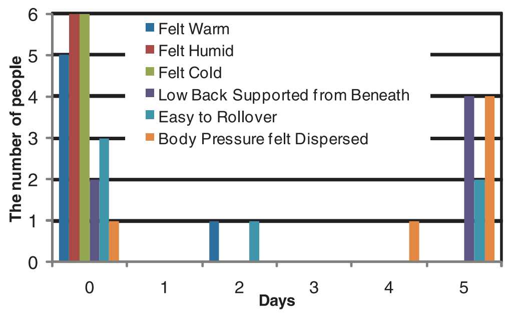


Fig.19 Sensory evaluation results of Next Generation Foam.

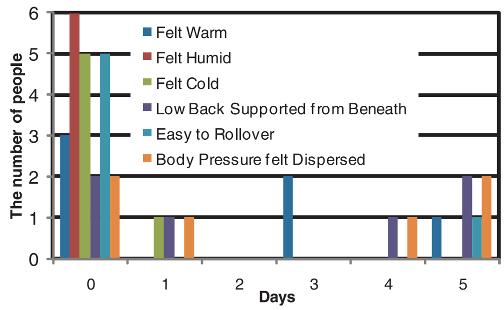


Fig.20 Sensory evaluation results of VE Foam.

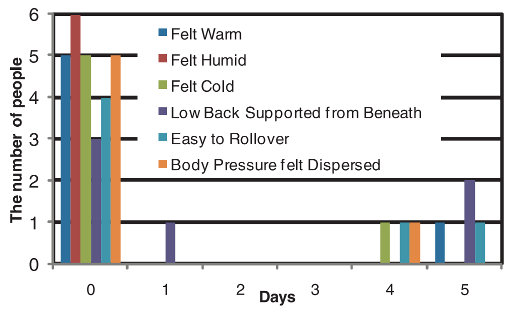


Fig.21 Sensory evaluation results of HR Foam.

As for the next generation foam, the number of the people who had the feeling of the Low Back Supported from Beneath, and Body Pressure Felt Dispersed were more than those of other mattresses. It was also clear that the next generation foam has excellent feeling and comfort based on the sensory evaluation.

4. Conclusion

We succeeded in the development of the next generation PU foam having high air permeability under compression, low temperature sensitivity, minimal hysteresis loss, and less bottoming out. The next generation foam has the unique characteristic that the foam cells compress uniformly when pressurized. We clarified the correlation between the physical properties of the flexible polyurethane foam and the evaluation of ergonomics for the mattress.

A single layer flexible polyurethane foam mattress made with the next generation foam provided:

1) Excellent body pressure distribution performance derived from the uniform cell compression.
2) Rollover ease based on the low hysteresis loss property.
3) Comfortable feeling in bed, resulting from high air permeability, low creep characteristics and low temperature sensitivity.

Furthermore, the correlation study between ergonomic data and flexible polyurethane foam properties would be useful for improving mattress performance.

5. Acknowledgement

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