Chair Development on the Basis of Body Pressure Distribution—A Research Effort*

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Abstract

Surveys and studies show that more and more employees perform high- or low-skilled white-collar work predominantly in sitting postures. Therefore, comfortable sitting plays an important role in reducing the risk of musculoskeletal disorders and other harmful effects. Research efforts focus on reducing these risks by designing ergonomic chairs with multiple adjustment possibilities, allowing the chair to fit to the user's body shape or assuring a dynamic seating where the user's lower body is in continuous movement. This article summarizes the results of a research effort that evaluated the effect of several factors on sitting comfort based on body pressure distribution. The effects of foam elasticity, foam layer arrangement order, and seat support elasticity were investigated as well as the chair seat type (kneeling chair, saddle chair). Results were used to determine the optimal chair cushion including the layered foam system and seat support type. On the basis of our findings a new ergonomic chair was developed combining the advantages of static and dynamic sitting.

Increasing surveys and studies underline the high rate of sitting during work. For example, Parent-Thirion et al. (2007) showed that more than 50% of employees in the European Union perform high- or low-skilled white-collar work, predominantly in offices. Humans' sedentary lifestyle is more and more common, leading to several musculoskeletal disorders. The increase of seated occupations and sitting times raises the risk factors in the development of low back pain and cardiovascular problems (Vink and Hallbeck 2012). Consequently, seating devices, i.e., chairs, must provide more comfort to diminish the negative consequences of prolonged sitting. Prolonged sitting combined with reclining and sleeping results in persistent contact of the body with a cushion of varying flexibility. Statistics reveal the importance of ergonomic sitting since the right furniture with proper use can help to reduce injuries and the so-called cumulative trauma disorders, which often result from repetitive movements for extended periods. From an ergonomic point of view, high comfort is related to well-being, a feeling of safety, and healthy sensation of the chair users. The enumerated subjective evaluation criteria can be fulfilled mainly by objective design specifications.

Consequently, the sitting comfort of furniture is the combination of the embedded materials, construction, and other design factors such as dimensions, tilt angles, etc., which may either add to or detract from the comfort of the finished product. Construction of upholstery, shape, and hardness of the sitting surface are also included in features

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Table 1.—Characteristics of polyurethane (PUR) foams.

Type of PUR foam	Color	Density (kg/m^3)	Compression hardness, kPa (DIN 53577)	Tensile strength, kPa (DIN 53571)
Normal, N2538	Violet	25	3.8	110
Normal, N3530	Gray	35	3	90
Flexible, R4342	Green	43	4.2	100

that determine sitting comfort (Kapica and Grbac 1998). The characteristics of upholstery are important for comfort and proper distribution of pressure; nevertheless, the basic factor of contemporary comfort is the specific pressure to the body, not the softness of the seat. This pressure is smaller when the contact surface of the human body is larger (Ergié 2002, Grbac and Ivelić 2005). Other scientific articles focused on revealing the relationship between sitting comfort and design specifications with the aim of reducing the discomfort of chair users. For example, Manfield et al. (2015) analyzed the discomfort in vehicle seats and concluded that foam composition can have significant implications on people undertaking journeys of long duration (>40 min in the conditions tested). Comparing different foam types, they determined the difference in overall seat discomfort. Small changes to foam composition were shown to affect the overall discomfort in the seat.

Vlaović (2010) conducted an experiment to determine the comfort index (support factor) of chairs obtained from elastic characteristics of materials in the seat of the chair. Upon examination of mechanical characteristic of chairs with polyurethane (PUR) foams, a better comfort index was found for chairs in which the subjective test evaluated them as uncomfortable (Vlaović 2010). In another study analyzing different types of seats, Vlaović et al. (2016) concluded that the chair with molded PUR foam is significantly more comfortable than the chair with springs, but statistically it does not differ significantly from the chair with a PUR foam cushion. According to Vink and Lips (2017) the form of the area contacting the body and the softness of this area influence the contact area between the body and the product. The pressure sensitivity of the skin and underlying tissue also plays an important role in comfort. Moreover, in seating design, to create a comfortable seat it is important to define the foam characteristics of the seat pan or the flexibility of the material underlying the foam (Vink and Lips 2017).

Materials and Methods

PUR foams are frequently used components of furniture upholstery nowadays. Combined with other flexible materials like springs, felts, belts, latex, or using layered foam structures of various firmness, they assure the comfort of seating and sleeping. Flexible PUR foams are soft, durable, provide good support, and maintain their shape; therefore they are preferred as filling materials for seating cushions and mattresses and can be produced to the density required by the manufacturer.

In a first series of measurements, open-cell PUR foams with different densities produced by Eurofoam Hungary Ltd were used. The selected foam types frequently used by Hungarian upholstery furniture producers belong to the Eurofoam Classic family, classes N and R. The properties of the selected foam types are presented in Table 1.

From the selected foam types, 600 by 600-mm sheets with a thickness of 20 mm were prepared and three-layered structures arranged in every combination of the foam types, resulting in 27 experimental setups. The layered structures were loaded with an anatomical seat loading pad according to standard EN 1728:2012.

Three types of support with different elasticities fixed on a wooden frame were placed under the foams: Bonell spring, sinusoidal spring, and plywood (Fig. 1). Between springs and foam sheets a thin protective felt was introduced. Forty-two experimental setups were fixed for measurements as combinations of the foam and support types. On each cushion structure loads of 250, 500, 750, and 1,000 N were exerted; the maximum load values were attained in 3 seconds.

For measurements the Tekscan's body pressure measurement system (BPMS; Conformat) was used with pressure-sensitive foils of size 488 by 427 mm containing 2,016 pressure points with a pressure range of 0 to 350 mmHg and accuracy of ±3.5 mmHg. Before using the BPMS measuring system the pressure sensor foils were calibrated with the help of a vacuum pump. After calibration the pressure maps of layered foam structures loaded with four compression force values were collected and analyzed with the software delivered with the system (BPMS Research 7.20) in the form of image (.fsx or .jpg) or short (0 to 200 s long) video files. On the recorded pressure maps, the contact surface area and peak pressure values were determined. The measurement setup is represented in Figure 2.

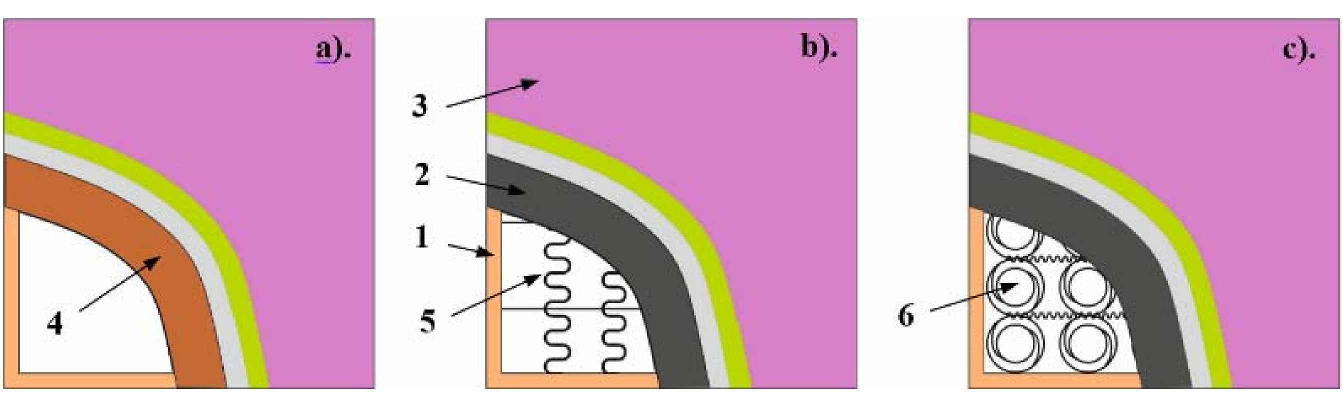


Figure 1.—Foam support system: (a) plywood (4); (b) sinusoidal spring (5); (c) Bonell spring (6) (1, wood frame; 2, protective felt; 3, foam layers).

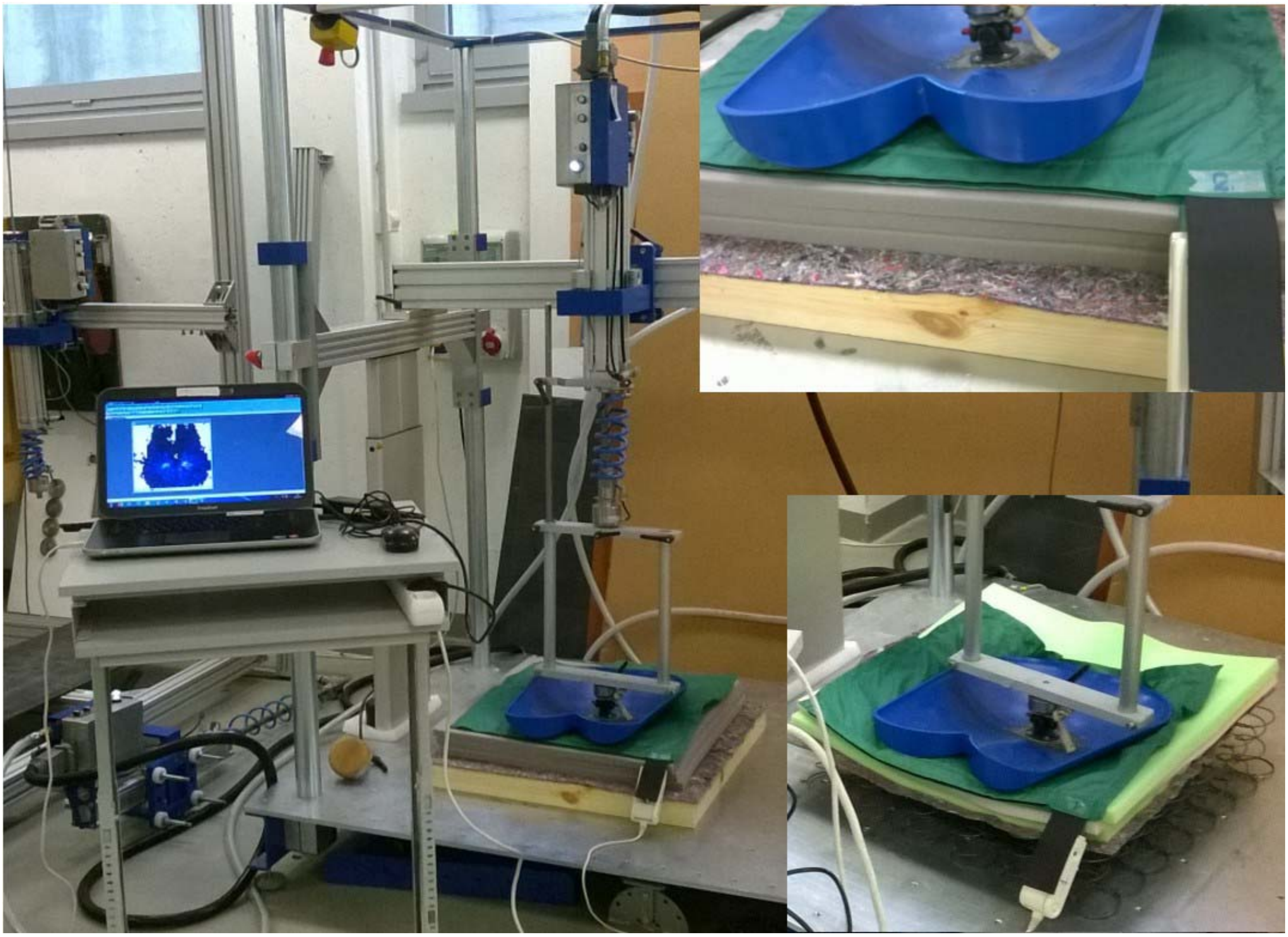


Figure 2.—The experimental setup.

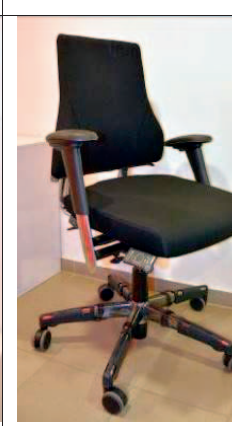
Aeron Remastered	**Thatsit Balance**	**Spinalis**	**Salli**	**Axia Smart**
				

Figure 3.—Analyzed office chairs.

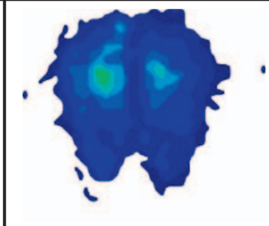
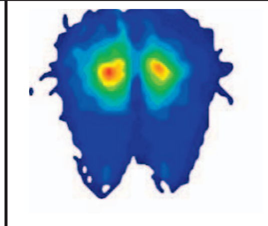
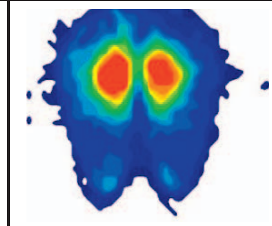
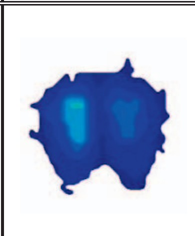
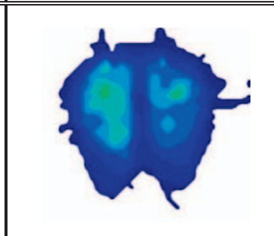
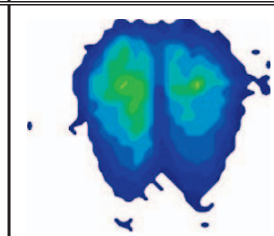
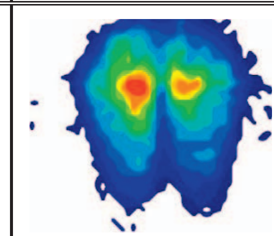
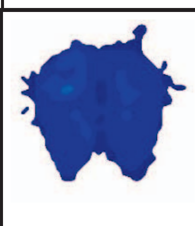
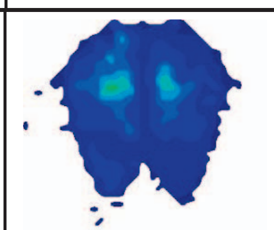
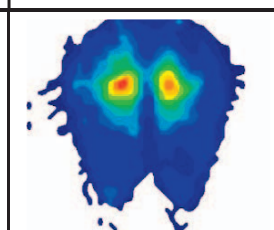
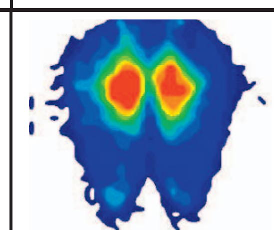
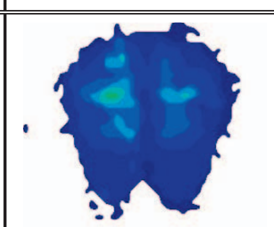
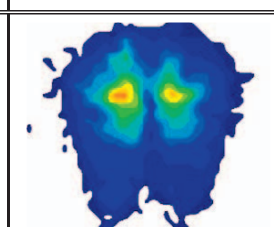
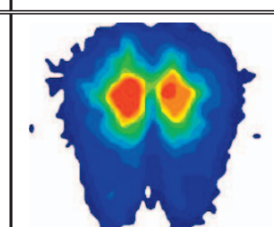
Pressure load, N	250	500	750	1000
Layered structure: **25-43-43 kg/m³**				
Contact area, cm²	563.61	905.29	1 058.06	1 125.16
Peak pressure, N/cm²	0.76	1.39	2.45	2.68
Layered structure: **43-25-25 kg/m³**				
Contact area, cm²	474.84	764.90	985.80	1 143.74
Peak pressure, N/cm²	1.03	1.30	1.63	2.62
Layered structure: **25-35-43 kg/m³**				
Contact area, cm²	595.61	937.29	1 076.64	1 165.42
Peak pressure, N/cm²	0.65	1.26	2.48	2.69
Layered structure: **43-35-25 kg/m³**				
Contact area, cm²	624.51	970.32	1 133.42	1 235.61
Peak pressure, N/cm²	0.74	1.27	2.27	2.69

Figure 4.—Pressure maps of layered foam structures with transient densities.

For a comparative study five work chairs were selected, each of them showing some special characteristics as follows (Fig. 3):

1. Aeron Remastered is the second generation of the famous Aeron chair designed by Bill Stumpf and Don Chadwick in 1994 and redesigned by the latter in 2016. Produced by Herman Miller, the Aeron chair is considered ‘‘the Dot-Com Throne.’’
2. The Norwegian industrial designer Peter Opsvik, known as the foremost designer of unconventional seating solutions, designed Thatsit Balance chair in 1991. Thatsit, the adjustable kneeling chair, creates balance in all postures, and offers support for seat, shin, and back simultaneously.
3. The Spinalis chair offers an active sitting, using a spring as an active element. The chair replicates sitting on a therapy ball, where the user constantly use the muscles to adjust to the seat’s slight movements.
4. The Salli saddle chair has a two-part seat and offers a body posture similar to that when horse riding. The

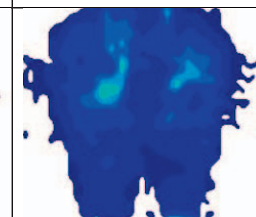
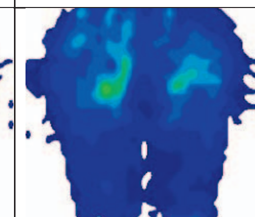
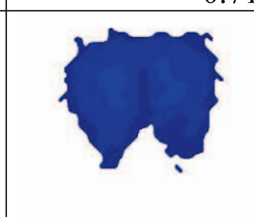
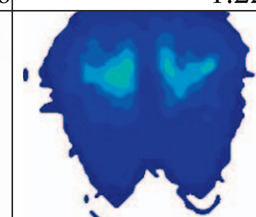
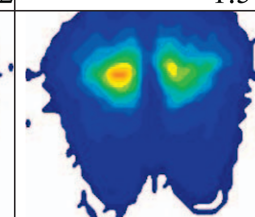
3 layered structures	250 N	500 N	750 N	1000 N
Bonell spring				
contact area, cm^2	717.4	1180.0	1462.7	1613.4
peak pressure, N/cm^2	0.47	0.64	0.93	1.18
Sinusoidal spring				
contact area, cm^2	693.7	1140.6	1384.3	1491.6
peak pressure, N/cm^2	0.71	0.96	1.22	1.51
Plywood				
contact area, cm^2	632.8	1033.3	1266.6	1378.1
peak pressure, N/cm^2	0.53	0.80	1.20	2.30

Figure 5.—Influence of support type and load on pressure distribution.

upright position of the pelvis supported by the sitting bones assure a good back posture and free movements of limbs and back.

5. The Axia Smart office chair developed by BMA Ergonomics teaches the users to sit better. The pressure sensors built into the seat and back monitor the user's sitting habits and warns the users in case of unhealthy postures.

Results and Discussion

The pressure distribution maps were recorded for all foam layer combinations, cushion variations, and chair types at the set force values. The results were analyzed on the basis of the contact area, peak pressure values, pressure dispersion, pressure intensity of different zones, etc. Figure 4 presents the pressure distribution maps of heterogeneous structures when two layers of the same low- or high-density foam sheets are combined with a third one of opposite density. In the case of high-high-low and low-low-high stratification the contact areas are very similar at any loading forces, but if the lower-density foam layer is placed on the bottom the pressure is more uniformly distributed; the pressure gradient steepness is smaller. From a seating comfort point of view, we found the best solution when a 43 kg/m^3 density foam layer is placed on two 25 kg/m^3 density layers.

The influence of a transient layer with a density of 35 kg/m^3 placed between the low- and high-density layers is shown in Figure 4. The contact areas are maximum at all load values when the high-density foam layer is placed on top, but the peak pressures are higher and pressure distribution is worse compared with the 43-25-25 kg/m^3 structure. From a pressure distribution perspective, the effect of a transient layer is marginal. Loading the three-layered foam structures with a load of 1,000 N led to a peak pressure of 2.69 N/cm^2 in almost all loading cases, which demonstrates that the loading pad compressed the foam layers completely and was supported by the test rig's hard base. This means that a 60-mm-thick layered foam system using foams with 25-35-43 kg/m^3 densities cannot attenuate completely the pressure exerted by a person of 100 kg weight. The maximum peak pressure at 750-N load was 2.61 N/cm^2 and obtained by using a homogeneous mid-density foam structure. At 500 N the highest value was 1.58 N/cm^2 on a structure composed of foam layers having 35-35-25 kg/m^3 density values. At the lowest load rate, the peak pressure was 1.12 N/cm^2 when a 25-25-25 kg/m^3 configuration was used.

In Figure 5 the influence of support type and load on pressure distribution is presented. At lower loads the differences between supports are more moderate; the sinusoidal spring shows the lowest contact area and similar peak pressure as the plywood support. When using higher loads there are no significant differences between the two

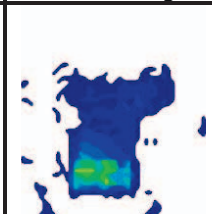
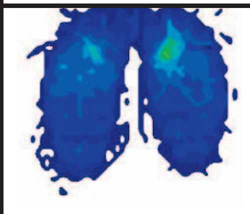
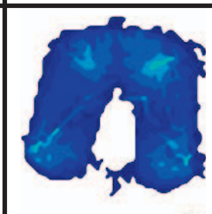
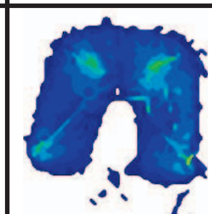
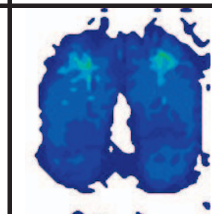
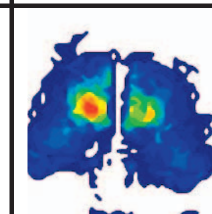
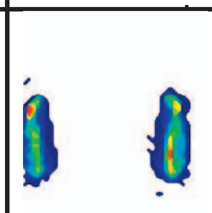
	Aeron Remastered	Thatsit straight	Thatsit forward	Spinalis forward	Salli forward
Back					
P_{max}, N/cm2	0.92	2.05	0.45		
A, cm2	792.8	584.3	219.9		
Seat					
P_{max}, N/cm2	1.89	1.32	1.42	1.38	2.49
A, cm2	1196.4	1186.1	1129.3	1244.90	1048.8
Knee					
P_{max}, N/cm2		1.38	2.59		
A, cm2		102.2	314.8		

Figure 6.—Influence of leaning on pressure distribution maps for a female subject.

contact areas; however, the peak pressures are 30% higher. The Bonell spring support assures the highest contact areas in all cases and the lowest peak pressures near the ischial tuberosity.

The softness of the top layer and firmness of the bottom layers combined with a Bonell spring support offered the best comfort of the system with the lowest peak pressures and uniform pressure distributions. The foam layers could dampen the effect of the hard plywood support. Even though no differences between contact areas were observed at increased loads using the sinusoidal spring support, the peak pressures decreased significantly. The pressure contact area is underestimated by the standard loading pad in the case of all four support types, even in the case of a subject with low body mass index. Opposite to the contact areas the peak pressures are overestimated by the pad except the moulded plywood seat pan where the pressure is underestimated; the pressure difference is much accentuated in the case of the flat hard support, attaining 72%. The alterations between real subjects and standard loading pad are due probably to the stiffness of the pad material (hard plastic) and the more flexible human muscles, the latter spreading more on the surface and attenuating the pressures better. In the case of normal-weight persons sitting on Bonell springs or sinusoidal springs the difference between contact areas is maximum 5% and between peak pressures reaches 21%.

The influence of subjects' body build on seat and back pressure distribution was investigated using the same sensing foil measurement system. From the pressure maps the contact area and peak pressure values were determined. The effect of leaning forward on the pressure maps is represented in Figure 6. In the case of the Thatsit chair the female subject slightly attaches the back, whereas the male subject does not attach at all. On the seat there are no considerable changes in area and peak pressure. By leaning forward the chair tilts ahead and the female user presses the knee pads with 2.59 N/cm^2, which is almost double the original value. Leaning forward does not have considerable effect on the contact area of the seat pan, but the peak pressure decreased slightly.

Contrary to conventional office chairs the pressure did not increase in the front edge zone when subjects leaned forward because of the tilting of the whole Thatsit chair and because of the bending of the seat pan of the Spinalis chair.

Conclusions

When homogeneous foam structures were used the lowest-density foams showed not just smaller contact areas indifferent of the selected loading forces, but a more even compression stress distribution. In the case of heterogeneous stratification, the lowest pressure values were determined for

Figure 7.—A newly developed chair model assuring higher comfort by segmented and flexible seat and back.

the high-low-low density configuration. Placing a transient foam layer between high- and low-density foam sheets did not indicate any significant attenuation. The lower peak pressure values do not always relate to a higher contact surface or even pressure distributions. Even though a hard anatomical loading pad was used for measurements, a more-or-less accentuated antisymmetric pressure distribution between left and right zones was observed. On the basis of the recorded surface contact areas and pressure distribution maps an optimal layered cushion can be developed. For an average user a layered system composed of 35-25-25 kg/m^3 density foam sheets or 43-25-43 kg/m^3 sheets assures a more uniform and wide pressure distribution, leading to a higher comfort sensation. The effect of support on the contact area and peak pressure was confirmed. The peak pressure attenuation depends on the applied load too; at higher pressure forces (500 N, 1,000 N) the damping effect is more accentuated. The Bonell spring support with its highest elasticity demonstrated the best combination of the analyzed variables from a comfort point of view.

The results obtained within the present study demonstrated that office chairs providing diverse seating postures focus on certain ergonomic and comfort aspects. Some highlight the importance of lumbar support; others put accent on active or upright seating; some others emphasize the significance of body support in each posture. The body pressure distribution analysis revealed that considerable pressure is exerted on knee pads when the subject tilts forward; the peak pressure values do not increase in the front zone when the seat pans are flexible. Based on the research results, a new chair was designed with multiple flexibility provided by materials, parts, shapes, and joints (Fig. 7).

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Literature Cited

Ergié, T. 2002. Contribution to research in pressure distribution on contact surfaces. Doctoral dissertation. University of Zagreb, Croatia.

Grbac, I. and Ž. Ivelić. 2005. Upholstered Furniture. 1st ed. University of Zagreb, Faculty of Forestry, Academy of Forestry Science, Zagreb, Croatia.

Kapica, L. and I. Grbac. 1998. Construction principles of ergonomic furniture intended for sitting and lying. Furniture and healthy habitation. *In:* Proceedings of the International Conference UFI-Paris, Zagreb, Croatia. pp. 53–58.

Mansfield, N., Sammonds, G., and Nguyen, L. 2015. Driver discomfort in vehicle seats – Effect of changing road conditions and seat foam composition. *Appl. Ergon*. 50:153–159.

Parent-Thirion, A., M. E. Fernández, J. Hurley, and G. Vermeylen. 2007. Fourth European Working Conditions Survey European Foundation for the Improvement of Living and Working Conditions. Dublin.

Vink, P. and S. Hallbeck. 2012. Comfort and discomfort studies demonstrate the need for a new model. *Appl. Ergon*. 43:271–276.

Vink, P. and D. Lips. 2017. Sensitivity of the human back and buttocks: The missing link in comfort seat design. *Appl. Ergon*. 58:287–292.

Vlaović, Z. 2010. Support factor of office work chairs. Proceedings of the 8th International Ergonomics Conference. Zagreb, Croatia. pp. 1–8.

Vlaović, Z., D. Domljan, I. Županić, and I. Grbac. 2016. Evaluation of office chair comfort. *Drvna Ind*. 67(2):171–176.