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MODELLING AND SIMULATION OF SOME PLANTAR ORTHOTIC COMPONENTS BEHAVIOUR

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Abstract: *The paper describes a research stage for manufacturing some plantar orthesis with for progressive correction of different foot deformities, focusing on prototyping materials. Two types of materials are taken into account: the first one refers on ABS plastic, the main advantage referring to prototyping precision and efficiency, especially for obtaining of any orthotic plantar components with role for progressive foot deformities correction. The second one refers to low-cost silicones, besides having the advantages of a high elasticity and prototyping efficiency. Both typed of new materials proved to be adequate by the point of view of strength and comfort when wearing shoes with orthopaedic insoles, from such of tested materials.*

Key words: *materials, silicone, ABS, load, orthesis, plantar.*

1. General Considerations

The problem of studying the properties and behaviour of the materials used for manufacturing of prostheses and orthesis has been increasingly developed in recent years. The issues of interest consist, on the one hand in their biocompatibility and, on the other hand, the degree of resistance to static and dynamic loads that would be subject during their use [5].

A special case represents the prosthesis and orthesis for upper and lower limbs, when various static and dynamic loads, may occur, fact that implies a careful study of the materials used in their manufacture [4].

Besides the problem of resistance of materials, another aspect, at least of important, refers to biocompatibility and comfort that they provide when wearing the prosthesis and orthesis. The issue of comfort while wearing materials provided, is even more important in terms of external orthesis such as for lower limbs [2].

Fig. 1. *Examples of foot orthesis: a); b) plantar cushions (textile materials); c) foot orthesis for Hallux correction (plastic and textile materials)*

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A special case refers to the plantar orthesis, to correct certain deformities such as flat feet, pronounced arch, Hallux, Valgus etc. In this case, materials like: special silicones, special plastics, antiperspirant textiles are most commonly used (Figure 1).

2. Proposed Materials for Prototyping

One of the great issues of our research in a post-doctoral project (on the optimisation of orthopaedic shoes) was to identify and test new materials, low cost, having the same qualities specified in section 1. Therefore it was taken the question: Could be used low-cost silicones or plastics in combination with special prototyping plastics for orthopaedic items manufacturing? Another issue would be the strength of such of materials in static and dynamic loads, equivalent to those of everyday life (standing, walking or running).

In a first research stage, two types of low - cost materials were identified, which may be successfully used in combination with textile materials [4], [6]. The first category refers to sanitary silicones, stored in tube that could be used for manufacturing different farms and types of plantar supporters.

Fig. 2. *Example of the arrangement of samples on sanitary silicone insoles on the shape memory textile insoles*

This could be possible through technology of stamping, according to the feet mold soles providing from the concerned subjects. These materials could be used in combination with textile antiperspirant foot insoles, to ensure the wearing confort (Figure 2).

Their cost was estimated to be about 60-70% from the cost of the special siliconic materials used currently for foot insoles manufacturing.

As a result, the main issue is: Could be used such of materials for foot insoles regarding the comfort and compatibility?

The second category of materials that could be used for orthopaedic shoed manufacturing refers to ABS plastics. The reason would be that these materials could be used for any special components with role of feet plantar diformities correction and these allow to obtain components via 3D prototyping procedure. In this case the main problem is to know if all categories of plantar orthotic components could resist for static and dynamic loads (similar to those in the cases of walking, standing or running).

As a result, for both category of new identified materials, it was taken the questions: on the firts side to ensure the confort, in case of sanitare silicones and, on the other side, the strength, in case of ABS plastics.

3. Materials for Prototyping

In terms of new identified materials evaluation, the following research stages were established [3]:

- identifying some persons with plantar diseases;
- making the fingerprint templates for identified persons having some foot diseases;
- fingerprint scanning and CAD virtual models obtaining;
- CATIA modelling of the orthotic elements, from virtual models reference.

For the first step, more young subjects (20-40 years) were tested: it was evaluated the plantar pressure in static mode (when standing) and in dynamic mode (when walking). The procedure was applied, using a Footscan plate high resolution, incorporating 65536 piesoelectric sensors.

In Figure 3 is presented an example of plantar fingerprints, in terms *pf* feet pressures charts.

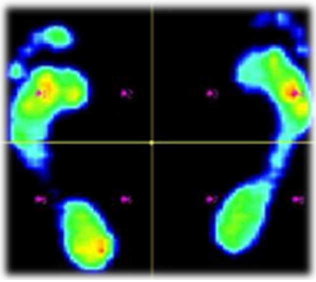


Fig. 3. *Feet fingerprints when standing, providing from one of the tested persons, as charts of plantar pressures distribution*

For each tested person, a plantar pressure distribution chart for both static and dynamic mode (when standing and when walking) was generated. Due to a statistical data processing providing from the generated pressure charts, it was possible to determine the differences in pressures, specific to the same plantar are, from one person to another.

Applying this procedure, two special persons were identified to have some plantar diseases: the first one presented a flatfeet, low degree, on the left foot and the second presented a pronounced arch, low degree, also on the left foot.

The next step was to provide the fingerprint molds for both identified persons (Figure 4).

Fingerprint scanning and CAD virtual models obtaining was the next step of the research, using a portable scanner based on LASER beam radiation.

The generated CAD models were saved as .STL and then exported to CATIA software environment, to be furtherly processed. The exported models were converted into continuous reference plantar surfaces to which some orthotic components could be modeled in CATIA (Figure 5b) [1], [7], [2].

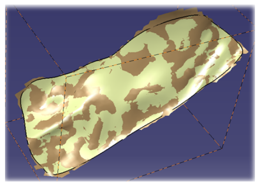
a)

b)

c)

Fig. 4. *Stage of molds: a) casting and levelling the plaster layer; b) fingerprinting; c) mold obtaining*

a)

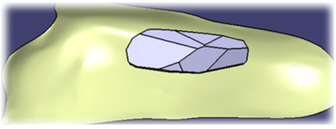


b)

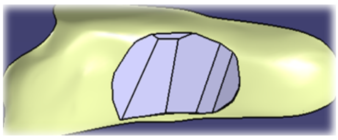
Fig. 5. *Scanning and CAD model obtaining procedure for one of the two plantar molds: a) scanning procedure; b) CAD model obtaining*

After that, the next step consisted into CATIA modelling orthotic elements, from virtual models reference.

For modelling, successive operation (extrusion, cutting, hole, Boolean etc.) were performed [7]. These referred to each component specific to one of the plantar areas (for the metatarsals, median area, inner arch, heel) (Figures 6 and 7).

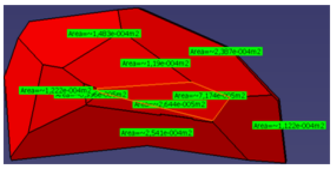


a)

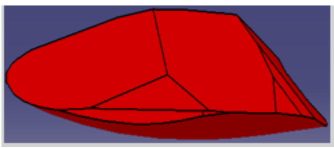


b)

Fig. 6. *Examples of plantar orthesis components modelling, in case of the person with flat foot: a) for the inner arch; b) for the entire arch*



a)



b)

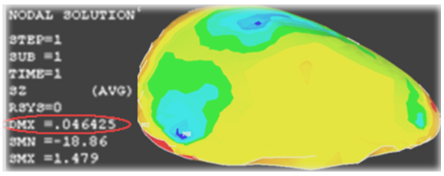
Fig. 7. *Examples of plantar orthesis components modelling, in case of the person with pronounced arch: a) for metatarsals; b) for heel area*

It was envisaged that each modeled component to be furtherly prototyped on a 3D printer, using ABS plastics, as material. To complete the plantar orthoses, these components could be incapsulated in siliconic and biocompatible items, to increase the comfort and also to ensure the plantar correction.

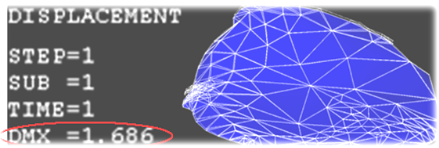
4. Materials Testing Conceptually Static and Dynamic Behaviour

Once modeled the items, in view of their prototyping, the main issue was to simulate their behaviour for different loads, in static and dynamic mode, similarly with real situations (standing, walking, running etc.). The simulation involved the case in which the components would be prototyped in ABS plastic, the main parameter being the bending and compression strength.

For the simulation, ANSYS software environment was used, the finite element method being applied (Figure 8). Lower regions of the elements could be considered as support surfaces. As a result, on the considered surfaces, were imposed fixing constraints. The upper areas were considered to be in contact to the foot sole. For this reason, on this areas, it was simulated the application of compressive and bending forces, specific to real cases of orthopaedic shoes wearing (standing, walking, running).



a)



b)

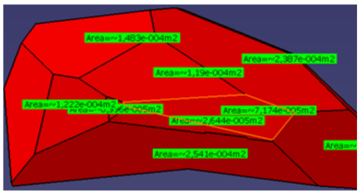
Fig. 8. *Behaviour simulation in ANSYS for a modelled component corresponding to inner plantar arch: a) in static mode (standing); b) in dynamic mode (running)*

To ensure that the components would resist to any loads, specific to all situations (static and dynamic), was held to a resizing and a remodeling of the component, to be then simulated in ANSYS. The most obvious example concerning the bending strength refers to the prototyping items specific to the metatarsals area (Table 1).

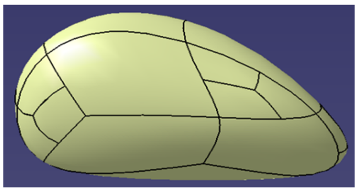
Table 1

Redimensioning of a modelled component specific to the metatarsal area, according to the simulation results

Item dimensions		
Length *L* [mm]	**Width *b* [mm]**	**Height *h* [mm]**
22.56	*43.86*	*3.76*



a)



b)

Fig. 9. *Converting procedure into a file compatible with the 3D printer, for a modelled component corresponding to the metatarsal area: a) before converting; b) after converting*

After re-dimensioning, for each component, the same simulation procedure was resumed. Ensuring that the resized component will resist to the static and dynamic loads, using CATIA environment, it was converted as into a file compatible to the 3D printer (Figure 9).

The simulation results on the re-dimensioned components behaviour by the point of view of resistance on static and dynamic loads were synthesised into numeric tables. Such a table was prepared for each modelled and simulated orthotic component in ABS plastic (Table 2…5).

Maximum admissible stress (σ) 60 MPa.

In green are presented the values for which the component will correspond and in red are shown the values for which it does not correspond by the point of view of strength.

It could be observed that, the metatarsal component could yield in case of jumping from heights greater than 0.3 m. When resizing elements orthotic items, in order to analyse the behaviour in static and dynamic loads in the new cases, it was imposed the two conditions in terms of re-dimensioning (1 and 2):

$$V_r \le 1.2 \cdot V_i \,, \tag{1}$$

$$h_r \le 1.2 h V_i \,, \tag{2}$$

when V_i and h_i represents the initial proposed medium volume and thickness high for simulation and prototyping for each plantar component, in ABS plastic and V_r and h_r represents the medium volume and thickness high for the same components after resizing.

The condition was imposed not to affect the comfort when wearing the orthopaedic shoes, due to some prototyped components in ABS plastics, with too high thickness. The constraint was established experimentally, for 3 samples of prototyping elements, for each plantar area.

The prototyped in ABS components could be then used in special orthopaedic insoles, as special core elements for any plantar diseases progressive correction.

For this, the next step was to insert the prototyped ABS components into silicone pockets for shock absorption and for comfort increasing. The silicone pockets prototyping was possible, due to the feet conformation (using the plantar molds) and ABS elements form.

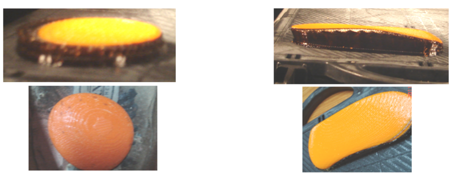
Simulation results on the modeled item specific to heel area Table 2

Element type	Simulated case	Type of load	Distributed load on the orthesis element, *R* [N]	Simulated stress, σ [MPa]	Simulated deformation, *f* [mm]	Maximum admissible deformation, f_{max} [mm]
For heel area	Standing	compression	43.6	0.0472	0.000112	0.254
	Walking		54.37	0.059	0.00014	
	Running		459.26	0.497	0.00117	
	Dancing		210.34	0.228	0.000538	
	Driving	-	25.05	0.0238	0.0000641	
	Jumping from: 100 mm	shock compression	13980.82	15.128	0.03573	
	200 mm		19771.87	21.416	0.0506	
	300 mm		24215.49	26.237	0.062	

Simulation results on the modeled item specific to metatarsal plantar area Table 3

Element type	Simulated case	Type of load	Distributed load on the orthesis element, *R* [N]	Simulated stress, σ [MPa]	Simulated deformation, *f* [mm]	Maximum admissible deformation, f_{max} [mm]
Meta-tarsal plantar area	Standing	compression	70	0.077	0.000147	0.3033
	Walking	compression and strees	98	0.886	0.04168	2.4387
	Running		465	4.2	0.198	
	Dancing		224	2.834	0.1334	
	Driving	compression	343	0.303	0.000619	0.3033
	Jumping from: 100 mm	shock compression	64261	37.919	0.116	
	200 mm		90878	53.624	0.16403	
	300 mm		111303	*65.677*	0.2	

After that, the manufactured pocket (containing ABS and silicone elements) was encapsulated into antiperspirant textile insoles (Figure 11).



a) b)

Fig. 10. *Prototyping of some plantar orthopaedic items: a) for heel area; b) for inner arch area*

Based on the favourable simulation results obtained due to the orthotic components resizing, the next step was their prototyping, using a 3D printer in ABS, high temperature ($T = 260$ °C). Samples of plantar orthotic elements during prototyping can be seen in Figure 10.

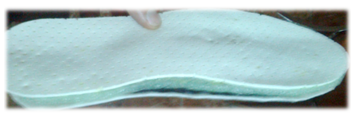


Fig. 11. *Obtaining the orthopaedic insole for progressive plantar correction, in case of the person with flatfeet*

Table 4

Simulation results on the modelled item specific to metatarsal plantar area

Element type	Simulated case	Type of load	Distributed load on the orthesis element, *R* [N]	Simulated stress, σ [MPa]	Simulated deformation, *f* [mm]	Maximum admissible deformation, f_{max} [mm]
For heel area	Standing	compression	68.23	0.066	0.000112	0.26
	Walking		76.37	0.074	0.000125	
	Running		462.3	0.4475	0.000758	
	Dancing		216.7	0.21	0.000355	
	Driving	-	-	-	-	
	Jumping from: 100 mm	shock compression	8661.74	8.384	0.0142	
	200 mm		12249.55	11.85	0.02	
	300 mm		15002.58	14.523	0.0246	

Simulation results on the modeled item specific to median plantar area Table 5

Element type	Simulated case	Type of load	Distributed load on the orthesis element, *R* [N]	Simulated stress, σ [MPa]	Simulated deformation, *f* [mm]	Maximum admissible deformation, f_{max} [mm]
For heel area	Standing	compression	86	0.0296	0.0000567	0.112
	Walking		93	0.0317	0.0000617	
	Running		465	0.146	0.000309	
	Dancing		223	0.0759	0.000121	
	Driving	-	348	0.1096	0.000231	
	Jumping from: 100 mm	shock compression	41637	13.956	0.02424	
	200 mm		58884	18.549	0.03914	
	300 mm		72118	22.718	0.04794	

5. Materials Testing by the Point of View of Wearing Comfort

Regarding the comfort when wearing orthopaedic shoes, the main issue was to know if using other prototyping components for plantar orthesis, manufactured by sanitary silicones could ensure the necessary comfort. For this reason, on both persons having plantar diseases, the following research was made: Each one wore during two months orthopaedic shoes containing insoles for plantar correction; the insoles contained both prototyped items in ABS and components prototyped in sanitary silicone, encapsulated in two antiperspirant textile insoles.

It was found that the sanitary silicones and ABS components did not affected the comfort when wearing the orthopaedic shoes during the two months, this applied for both persons.

6. Results and Discussion

The research led to the conclusion that both types of materials (ABS plastics and sanitary silicones) could be successfully used for prototyping and manufacturing orthopaedic orthesis for the two subjects with plantar diseases.

The main advantages of the two proposed materials are low costs for sanitary silicones, ease of use, endurance and flexibility for ABS plastics.

Acknowledgements

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