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A KNOWLEDGE-BASED DESIGN PROCESS FOR DIABETIC SHOE LASTS

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1. Introduction

Doctors' experience and knowledge confirm the need to understand the role of medical and clinical factors in putting the foot at risk of ulceration. Many foot parameters, even if considered to be important in elevating the risk of ulceration, are not in direct relation with footwear features, and so cannot be defined. For instance, the Ankle Brachial Pressure Index (ABPI) is a characteristic parameter for diabetic people, but there would be no need to scale a shoe feature to the scale of ABPI values.

Diabetes is a growing health problem round the world. The World Health Organization estimates that in 2030 more than 334 million people will suffer from diabetes (*www.who.int/diabetes*). Today, the main problems for people with diabetes are due to the complications that such a condition generates. One of the most relevant complications is called "diabetic foot". Peripheral neuropathy, a loss of feeling in the extremities, renders these individuals unaware of sores which develop on their feet until the wound becomes infected. Then, due to other diabetes-related complications, the infection often defies healing and eventually leads to the amputation of the foot. The main cause of foot ulceration in neuropathic diabetic adults is thought to be the presence of abnormally high plantar pressures secondary to neuropathy. It is evident that a reduction in the number of amputations can be achieved if it is possible to effectively prevent foot ulceration. Early diagnosis through continual foot monitoring can be made. However, the best approach is to wear suitable personalized shoes which avoid the causes of ulcerations. Despite the necessity, there is no full user-cantered footwear development due to the difficulty in simultaneously taking into consideration multiple design aspects such as foot shape and biomechanics, material performance for the upper, insole and outsole, and manufacturing methods. These factors affect cost, availability on the market, and variety in terms of aesthetics. In order to investigate this problem, a research program (SSHOES) has been developed and funded within the Seventh European Framework Program. It aims to develop a new paradigm and implement infrastructure for creating diabetes-oriented footwear, based on product demand differentiation and personalization in order to achieve high quality and customer satisfaction. Specifically addressed research topics are: 3D foot digitalization systems, footwear design tools dedicated to personalized biomechanical as well as asthetic aspects, adaptive production technologies, etc.

This paper is focused on the adopted approach related to the shoe last design, which is one of the most important components of the shoe design process. In particular the paper aims to:

- define a repeatable procedure in order to orient the scanned foot geometry and the last model in standard coordinate systems;
- define a set of meaningful measurements and points to drive the shoe last design phase;
- define a set of functionalities to support the shoe design phase using a general purpose CAD system.

The results regarding the implementation of the supporting software systems are shown. After a brief review of tools dedicated to shoe customization, the design approach will be firstly described. A prototypal design system implementation will be proposed in order to support personalized shoe last development. The main developed features consist in the possibility to input suitable geometrical values for the shoe last parameters from patients' data analysis deriving from sensors such as foot scanners and pressure measuring systems.

2. Advanced tools for footwear design

Over the last decade significant efforts have been made to transform the footwear industry from a labour-intensive activity to a knowledge-based manufacturing process. Modernizing this so called 'traditional industry' does not mean concentrating only on the style and design phase but it also means being able to master the whole product and process life cycle adding value (knowledge and intangible) to each phase of the shoe life-cycle. In order to achieve this goal, important innovations in engineering, information technology, materials, information and communication technologies, etc., are developed and adopted by this industrial sector. According to Boer et al. [Boer et al. 2004] footwear manufacturing has evolved from craft production in the middle of the 19th century to mass customization and personalization in the beginning of the 21st century where goods and services are more tailored to the specific needs and tastes of the consumers. There has been a growth in the need for more intelligent CAD systems and simulators as well as complete manufacturing solutions.. Therefore, several efforts are nowadays being made in making the shoe industry human-centered by developing new concepts for customizing or personalizing the final products [Leng et al. 2006]. Various specific CAD systems to create 3D virtual models of shoes have been developed [Raffaeli et al. 2008], [Smith et al. 2006]. They are mainly oriented to manage manufacturing processes such as upper cut, shoe sole molding or to marketing purposes. The creation of customized shoes has also been investigated in several research activities [Boer et al. 2007]. They deal with the digitalization of customer's feet by adopting non-contact 3D scanning systems and related range data elaboration software tools in order to provide a virtual foot model [Redaelli et al. 2005] or a set of meaningful cross-section measurements [Luximon et al. 2005].

Several approaches for the shoe last design have been proposed:

- deforming an existing shoe last into the customized one which matches with the scanned foot data through free-form deformation [Cheng et al. 1999], distance map or some other similar method [Bao et al. 1994], [Sambhav et al. 2011];
- using a CAD systems for designing ex-novo customized shoe lasts for the customer's feet and the chosen style [Luxymon et al. 2009];
- deforming a certain shoe last into the customized one which fits the scanned foot data based on the customer's foot features while maintaining its original style [Xiong et al. 2010].

These methods show two main gaps in the application on the diabetic foot. The first refers to the fact that design knowledge about style, comfort and preventive or corrective shoe functions must be embedded in the product in aprioristic manner. In other words, such approaches do not provide any means of supporting the design activity starting from patient data and curative needs.

On the other hand, existing approaches lack in considering how orthopedic technicians really work. The observation of the work of the operators shows that the shoe last selection phase is accomplished comparing the whole last shape only for stylistic reasons and specific parameters for the fitting and the illness preventive function. The current developed systems are not able to provide successful solutions such particular applicative sectors as diabetic foot.

When dealing with shoes for people who suffer from diabetes, there arise additional issues. Apart from the intrinsic factors of the illness, many extrinsic factors related to feet and footwear can influence the progression of diabetes and health (e.g. foot pressure, the foot movement in the shoe, lacing of the shoe, moisture permeability, insole geometry, stiffness and shock absorption properties, sole depth, pitch, stiffness and how these alter over the length of the shoe). Each of these extrinsic aspects requires data and information from the specific patient to enable appropriate footwear personalization.

Furthermore, changes of footwear performance over time and/or patients' use and ways of moving can affect the clinical efficacy of footwear. Several commercial systems (e.g. Vorum by Canfit, FootWizard by Otto-Bock, SOLETEC by Shoemaster, etc.) try to achieve a full customization of shoes and insoles for people with special needs. System interoperability, integration, performance, implementation of biomedical and biomechanical features and ease-to-use for non-expert users (e.g. health care professionals who work with patients with diabetes, orthopedics, etc.) are only some problems limiting their application.

The main practical problems to be considered are listed here:

- lack of suitable 3D modeling strategies of deformation to modify the last shape as the experts do manually;
- lack of criteria to model the insole and the whole shoe in according with the medical criteria;
- lack of advanced tools to manage heterogeneous geometric and non geometric data (clouds of points, surfaces, images, pressure maps, disease characteristics, etc.);
- the impossibility of capturing the foot in the desired position set up by the orthopedic technician;
- the right combination between the acquired foot geometrical data and the plantar foot pressure;
- the difficulty to design a proper insole in terms of shape and materials to unload specific foot zones.

In this paper, the research effort is dedicated to face the first cited problem: to facilitate the shoe last design through a virtual modeling system dedicated to the problems associated with diabetic foot.

3. Approach for shoe last design dedicated to diabetic foot

Bio-mechanical objectives have to be satisfied during the last design phase. This is only possible if a relation between objectives and a set of footwear design features (individual characteristics used to specify the design) is defined. For diabetic patients, the biomechanical objective of reducing plantar pressure under the 1st MTP joint can be addressed both using a rocker sole [Hutchins 2009] and modifying the last shape. The rocker sole reduces the motion of the metatarsal joints during walking. Its geometry is identified by the following footwear design features: rocker angle, apex position, apex angle, heel height and sole stiffness (Figure 1).

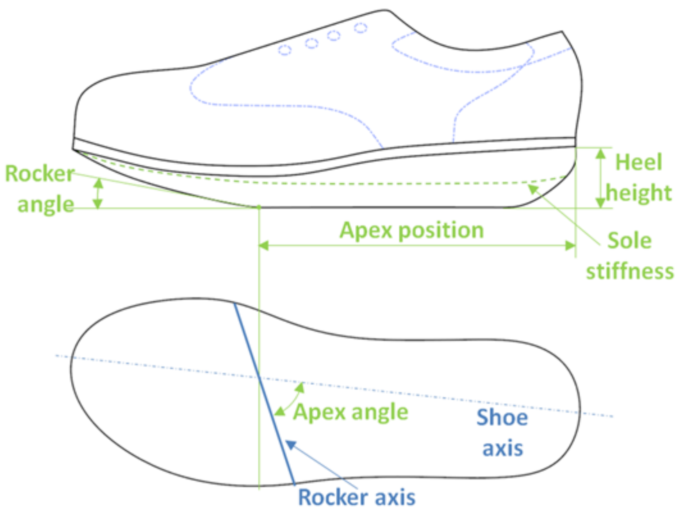

Figure 1. Footwear design features of a shoe for diabetic people

Table 1 reports a list of connections between footwear features and biomechanical objectives, reporting only those which have a direct influence on the last definition process. The third column contains the last geometrical parameters which need to be tuned in order to pursue the preventive and healing function of the footwear. Figure 2 reports a picture of the main last geometrical parameters and measures.

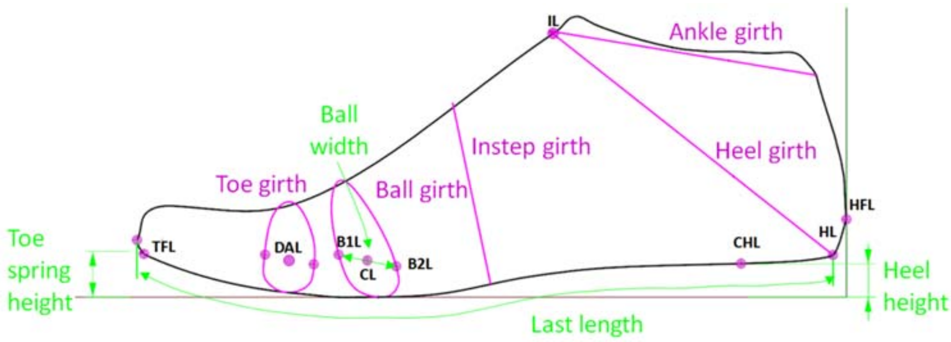

Figure 2. Last measures which have a direct connection to footwear features for diabetic shoes

Table 1. Relationship among footwear features, biomechanical objectives and last measures to be modified

Footwear feature	Biomechanical objective	Last parameters to be modified
Width of metatarsal heads, ball girth, instep girth, heel girth	Accommodate insole to release plantar pressure Minimise changes in foot shape during walking	Ball circumference Ball width Instep circumference Heel circumference
Total foot length, metatarsal width and navicular drop	Minimise changes in foot shape during walking Minimise shear loading on the forefoot	Last length Ball circumference Ball width
Toe box height, toe girth	Minimise pressure on dorsal aspect of the forefoot and toes Minimise pressure on the 5th metatarsal base	Toe circumference
Rocker sole: rocker angle, apex position, apex angle	Minimise pressure under 1st MTP joint and toe Minimise pressure under 2nd-5th metatarsal heads Minimise vertical shear loading at the posterior aspect of the heel Minimise pressure under the mid foot	Heel height Ball width
Toe spring	Minimise pressure under 1st MTP joint and toe Minimise pressure under 2nd-5th metatarsal heads Minimise vertical shear loading at the posterior aspect of the heel Minimise pressure under the mid foot	Toe spring height
Heel height	Minimise overpull on the Tendon Achilles and the pressure under the forefoot	Heel height
Size of shoe entry	Minimise pressure on dorsal aspect of the forefoot and toes Minimise vertical shear loading at the posterior aspect of the heel Minimise pressure on the 5th metatarsal base	Ankle circumference Heel circumference

3.1 Guidelines in the design process of diabetic lasts

The heel height represents the height of the back of the sole. It differs from the required heel height of the last, which is the actual height experienced by the foot in the shoe. The correct last heel height is computed combining the apex position, the rocker angle and intrinsic parameters of the chosen last, i.e. last length and toe spring. Heel height influences the tension of the Tendon Achilles, the pressure on the forefoot and the shear loading.

The apex angle determines a release of the foot pressure on the sole while walking. Such an effect must be facilitated providing a customized last shape in the metatarsal zone. Generally the ball width needs to be enlarged in order to accommodate an insole and provide more stability in case of

significant deviation of the apex angle from 90°. Higher values of these angles generally reflect a more serious pathology and those the need of a bigger space to accommodate a custom insole.
Multiple positive effects are reached varying the last circumferences. Ball, instep and heel circumference are required to cope with the space required for the foot and the custom insole. Moreover, they must guarantee limited changes in the foot shape during walking to avoid friction with the upper and shear loading. The enlargement of the toe circumference produces benefits in both the upper and bottom part of the forefoot. Finally, ankle circumference and heel circumference determine the size of the shoe entry and must be balanced with the pressure at the posterior of the foot.
The above considerations are the results of research on diabetic patients, but literature does not explain how a patient's biomechanical foot characteristics would interact with the design features in order to satisfy the biomechanical objectives (i.e. to minimize the plantar pressure). For this reason, experimental tests on diabetic patients have been conducted in order to gather knowledge. Relationships between patient biomechanical foot properties and the set of footwear design features have been established with the aim of pursuing the objectives presented above. Tests have been performed recruiting 100 participants using the following criteria:

- patients have been diagnosed with diabetes for at least 6 months;
- they are not suffering from any form of ulceration or other foot condition resulting from diabetes;
- they do not have a major foot deformity limiting activity.

16 pairs of shoes have been identified mixing footwear design features in a randomised order. Every participant wore each pair for 3-5 minutes. During this period they walked around until they felt comfortable in the shoes. In-shoe pressure levels were recorded as they walked over a 15m distance. The primary outcome of the record was the peak pressure under the 1st metatarsal.

3.2 Diabetic last design process

This paper proposes a set of integrated software tools for the diabetic last design. A specific design workflow is presented to obtain a customised last starting from the patient bio-mechanical parameters (Figure 3).
The first activity concerns measuring the bio-mechanical parameters of patients' feet by means of the gait analysis [Bogey]. In particular, doctors and clinicians assess the plantar pressure, the medical and shape parameters of the foot. A Knowledge Based tool is introduced to match the footwear design features and the bio-mechanical parameters. The KB system is connected to a database containing knowledge representing relationships between bio-mechanical parameters and footwear features. Artificial Neural Networks algorithms, such as the multi-layer feedforward neural network, have been used to manage this kind of knowledge. This approach has been widely used within the field of human movement research [Chau 2001].
Design workflow proceeds to a software tool used for retrieving lasts from a dedicated database and selecting the one to be used for the patient. The database contains:

- the geometry of the last, i.e. a mesh in .stl format;
- the characteristic measures (*last length, instep girth, ball girth, etc.*);
- the footwear design features (*heel height, apex angle*, etc.).

A search tool is used to retrieve lasts which will be transmitted to *InfoHorma (IH)* package. The 3D geometry of the digitized foot is also included. IH is a software tool used to measure both lasts and feet, using a rigorous methodology. Foot and last measurements are then passed to the search tool, which compares them and rejects the lasts which differ too much from the foot. Finally, remaining lasts are sorted according to the deviation, to determine the best fitting one.
The selected last, the foot geometry and the footwear features represent the input data of the software tool developed for the actual last design, called *LastDesigner (LD).* This module has functionalities which allow the last parameters to be met.
Once the design phase is completed, the obtained customized last is compared again with the foot in order to check that the changes fit with the patient's foot. If deviation between foot and last exceeds the tolerance admitted by the designer, adjustments can be performed. The obtained last is ready for milling and the other shoe parts (upper, outsole and insole) design activities.

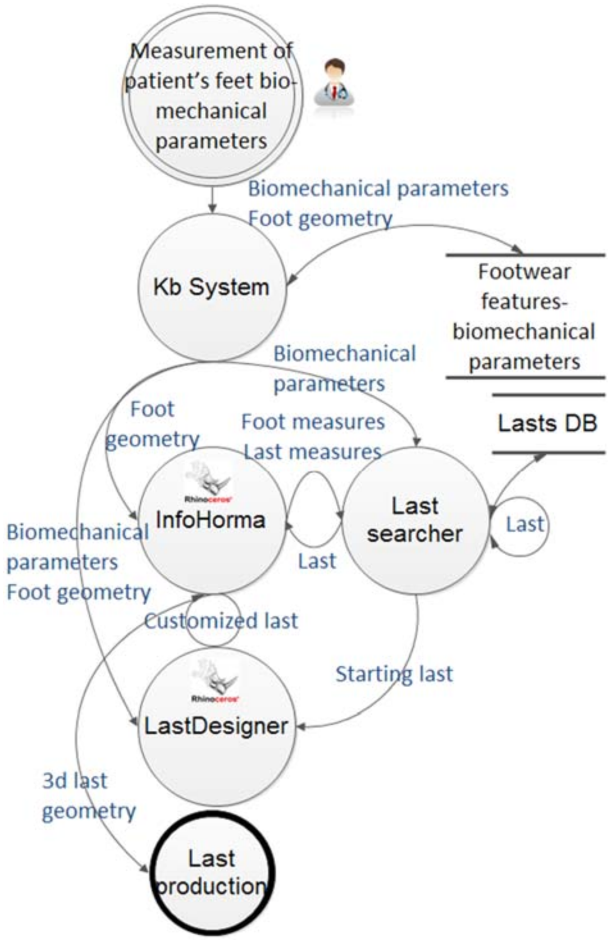

Figure 3. Shoe last design process for diabetic patients

4. Supporting systems for the diabetic last design

The architecture to support the design process is based on two dedicated software tools integrated within the same environment. In this way data exchange is improved and last design process is efficient. The integration has been based on Rhinoceros 4.0 by McNeel Inc., a commercially multipurpose CAD system. This platform hosts two specific plug-ins, namely *LastDeisgner* and *InfoHorma*. This solution allows the final user to gain advantages of both the dedicated functionalities and the 3D CAD system native commands.

4.1 InfoHorma

InfoHorma measures a pair of feet and lasts after orienting them using the same procedure. Three main groups of functionalities are defined:

- positioning and alignment of foot and last according to a protocol;
- calculation of meaningful points which are then used to measure foot and last;
- export of measures and geometries defined during the measurement process.

The alignment and measuring phase is possible thanks to the definition of characteristics points of the lasts and feet. While some of them are located on the geometry from its analysis (for instance the 1st and 5th metatarsal points are defined as the most prominent points along the y-axis, close to the metatarsal region), others are defined considering the foot/last anatomy and its proportions. These points are:

- *HL*: back most point of the last;
- *HFL*: posterior-most point of feather line;
- *TFL*: front-most point of feather line;

- *CHL*: heel seat centre of the last located on the foot-last sole axis at 15% of the effective last length (length of the corresponding reference foot plus the minimum allowance), measured from the HL Point;
- *B1L*: medial-most (internal) last point;
- *B2L*: lateral-most (external) last point;
- *CL*: midpoint of the line joining points B1L and B2L;
- *DAL*: midpoint on the toe section base, located on the foot-last sole axis at 85% of the effective last length, measured from the HL point;
- *IL*: intersection of last-foot longitudinal section (on the foot-last plane) with a line perpendicular to foot-last sole axis at 50% of effective last length, measured from the HL point.

Many points are located on characteristic foot and last axes, which consist of:

- *Machining axis*: the longitudinal axis used by last makers for the machining of lasts, corresponding to the turning axis of traditional turning lathes;
- *Foot-last axis*: the line passing through the Heel point (HL) to the Ball midpoint (CL);
- *Foot-last sole axis*: the foot-last axis projection onto the bottom surface of last or foot. This is the line along which the length measures of last and foot are taken.

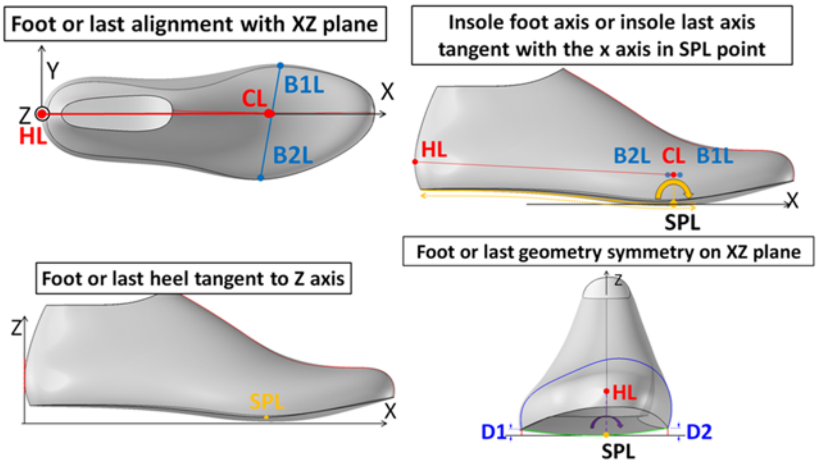

Figure 4. Criteria to univocally orient and position foot with last

Once last and foot mesh have been imported, points and axes are calculated and the alignment is performed according to the following steps (Figure 4):

- *Foot / last alignment with XZ plane*: the rear most prominent point of mesh, along the x-axis, is firstly calculated. The 1st and 5th metatarsal points are then calculated as the most prominent points along the y-axis. The axis connecting HL and CL points, called foot or last axis, has to be aligned with the x-axis;
- *Insole foot axis/ insole last axis is made tangent to the x-axis in SPL point*: first of all the foot insole axis and last insole axis must be calculated (they are two curves). They are calculated projecting respectively foot and last axis onto the insole geometry of foot and last mesh. The SPL point is calculated projecting the CL onto the foot or last insole axis. The foot or last insole axis must be tangent to the x-axis on the SPL point;
- *Foot / last heel is made tangent to the Z axis*: the rear most prominent point must be located on the z-axis;
- *Foot / last geometry is made symmetric to the XZ plane*: the curve calculated sectioning the mesh with a plane parallel to YZ passing on CL has to be symmetric with respect to XZ plane. Symmetry is guaranteed with a rotation around HL-SPL axis till D1 is equal to D2;

Once geometries have been aligned, the measuring phase is accomplished (Figure 5). Measurements are calculated as distances among points or curves length, sectioning the foot or last with specific planes. A team of researchers, doctors and technicians working in the footwear industry have been

questioned about typical measurements.
In the context of the diabetic shoe, the following ones have been selected as the most representative:

- *insole last length*: distance from the HFL and TFL points on the last sole machining axis;
- *toe spring height*: distance from ground plane of the TFL point;
- *heel height*: distance between the CHL point and XY plane;
- *ball width*: distance between ball points B1L and B2L projected on the ground plane (XY);
- *ball girth*: shortest perimeter passing through points B1L and B2L;
- *toe girth*: the intersection of the last with the plane perpendicular to the last sole axis on the DAL point, with the same torsion angle of ball section;
- *instep girth*: the intersection of the last with the plane raised at 50% of the effective last length minus the *heel back delta* measured from the HFL point and perpendicular to the last sole axis. Heel back delta is the displacement of HL point measured on the extension of the foot-last sole axis;
- *heel girth*: perimeter containing points HFL and IL of the last, following the shortest surface path;

Finally, the third group of functionalities is used to export section curves, points and measurements in a standard geometrical exchange format such as ".*igs*".

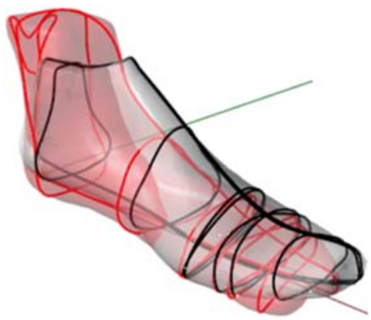

Figure 5. Foot/last geometries with relative measurements

4.2 Last designer for diabetic foot

The goal of the LastDesigner system is the definition of the model of a customized last for orthopedic purposes. The set of modeling functionalities includes foot and last points cloud data importing, last geometry creation as NURBS surfaces, last measure modification, exporting to milling devices and upper surface unrolling for leather cutting. Such functionalities have already been described in previous works [Raffaeli et al. 2006], [Raffaeli et al. 2009], [Davia et al. 2011].
In the context of the present work, LD has been further developed to support last design for diabetic patients. The main contribution is represented by a set of dedicated functionalities to modify the geometry of the last on the basis of the values of the specific last geometric parameters which are the output of the KB system and listed in Table 1. In case of more serious pathologies, LD also provides the possibility of manually operating on highly non standard last shapes which are required for feet affected by diabetes for a long time, e.g. in the case of amputations.
Three specific geometrical operators have been implemented to meet the desired last shape:

- *Heel height adjustment*: this command allows the heel height to be varied according to the rocker outsole parameters and maintaining the last volume and style;
- *Girth adjustment*: this command allows any last circumference to be varied controlling the areas where material is added or removed, i.e. internal/external or lateral/top. This is used for modifying toe, ball, instep, heel and ankle girths;
- *Last feather curve reshaping*: the last shape is modified as a consequence of feather curve modification. It is used for adjusting the last width and the toe box width.

The volume of the last is represented by three untrimmed NURBS surfaces: the *sole surface*, the *upper surface* and the *top surface*. The border between the sole and upper surface is referred to as *feather curve* while the upper is joined to the top surface by the *top curve*. The NURBS geometry is

notoriously determined by its degree, the knots vector and the position of the control vertices CVs. In particular, Cvs are used as an effective way to evenly modify the last shape while preserving its style and esthetic features. For this reason, the choice of the control vertices grid spacing is critical. After some testing, value ranges have been fixed to vary between 10 to 20 horizontal subdivisions and 30 to 40 vertical slices. Indeed, LD allows the grid to be spaced accordingly to surface curvature concentrating more points where the radius of curvature is inferior.
The operator to modify the shape are defined as three dimensional displacement fields to be applied to the control points. The field varies from zero at the boundary of a 3D domain to a maximum target value. The boundaries of the field are given by surfaces which are defined starting from last geometry accordingly with the type of modification. Maximum target value is drawn from the last measurement to be met.
Here follows more details concerning how the three required modifications are accomplished.

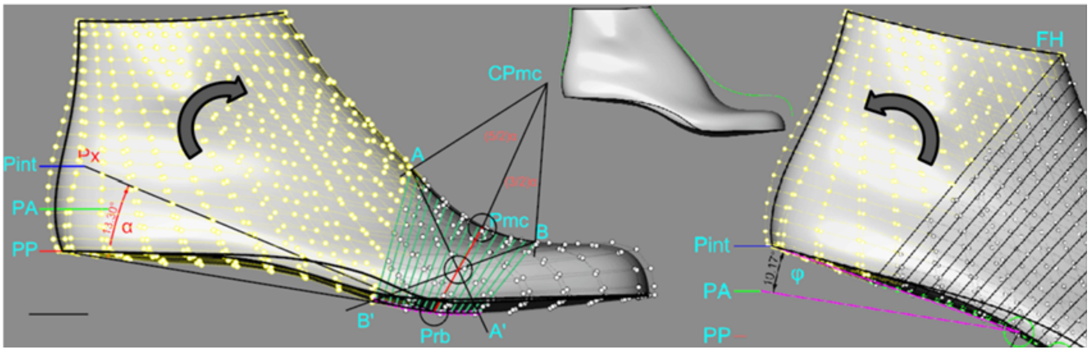

Figure 6. The two-stepped control vertices displacement field for the heel height modification

The *heel height variation* is reached in two steps as pictured in Figure 6. The first step is a rotation centered in the metatarsal area. This rotation brings the heel height from the level marked with *PP* to the intermediate level *Pint*. The second rotation is centered in a backward position and leads to the final desired heel level marked with *PA*. Currently each of the two steps is given by a composition of small rotations whose center moves along the last side profiles. The extension of the deformation volume is contained in the quadrilateral ABA'B' and is proportional to the angle of rotation α. Such variation produces a smooth displacement field and allows the last style to be preserved.

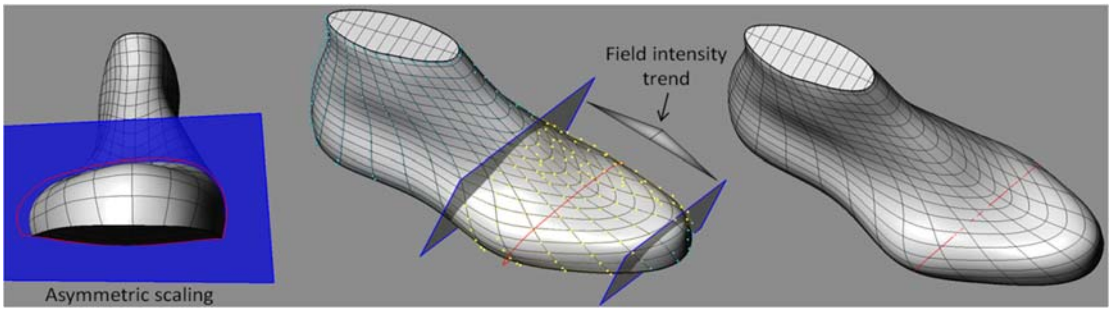

Figure 7. Ball girth asymmetric scaling which emphasizes the external side of the metatarsal area. The red curve previews the volume distribution on the target plane

Girth adjustment can be applied on any of the last modification circumference as defined by the IH module. Modification is driven by the intersection curve between the last and the girth plane (Figure 7). The curve is deformed in order to meet the desired length on the basis of an anisotropic scaling which emphasizes selected portions of the girth. The last surface modification domain is contained between two planes which are parallel to the girth plane. The translation field is iteratively applied to the surface CVs in order to approximate the modified curve profile. The field varies between the maximum on the curve plane and zero at the limit planes.

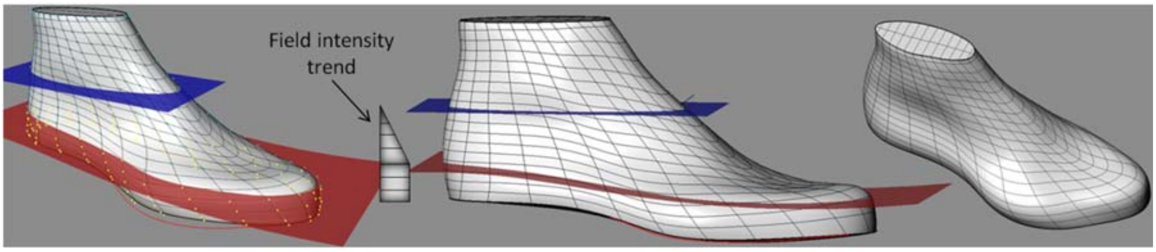

Figure 8. Feather curve shape modification

The *feather curve reshaping* works in a similar manner. Feather curve is initially modified to meet the desired parameters, i.e. last width and toe spring. The modification domain is split in three regions by two surfaces as in Figure 8. The lower surface is built from the extrusion of the side profile of the feather curve (red surface in the figure). An offset distance corresponding to the toe height is applied. The CVs falling in the region at the lower part of the surface are iteratively translated to meet the curve shape. The upper boundary surface is a plane positioned at the IL point level. Over the plane the modification is null, while in the central region the translation field is mitigated by the proportion of the distances to the two limit surfaces.

5. Case studies

The described approach has been developed in the context of the European project SSHOES and has been tested by a shoe maker and a university clinic. The SSHOES project (NMP2-SE-2009-229261, co-funded by the European commission according to the 7th framework programme) addresses the development and demonstration of new sustainable production capabilities for diabetic feet and fashion high added value consumer-centred product concepts, such as footwear and insoles.

5.1 Design system use

The database managed by KB system has been populated with data coming from 16 patients. In the experimentation phase, the last design process has been tested involving a clinic and shoe manufacturers. The clinic has been equipped with a 3D foot scanner, a baropodometric platform and a gait analysis system. For each patient, 3D foot geometries and pressure maps have been acquired for a complete gait. Data was transmitted to the shoe manufacturer to design and realize the last and the shoe. Using the KB system, the footwear design features has been calculated given the set of biomechanical parameters. Testing also involved the insole and outsole design phases, but they are not discussed here since they are beyond the paper scope. Deviation between foot and last measurements for a selected case is reported in Table 2.

Table 2. Comparison of last-foot measures for a selected test case (abstract of a more detailed measures list)

Measures	Last (mm)	Foot (mm)
Insole length	286	272
Toe spring height	17	-
Heel height	14	-
Ball width	109	107
Ball girth	262	250
Toe girth	232	227
Instep girth	259	257
Heel girth	352	347

5.2 Result discussion

The new last design approach proposed in this work has been compared with a traditional one in Table 3. Meaningful improvements have been highlighted in all phases, from the footwear design feature evaluation to the final foot-last fitting verification. Patients' biomechanical parameters analysis was excluded.

Table 3. Process time comparison between traditional and proposed approach

	Traditional process (minutes)	Proposed process (minutes)	Improvement (minutes)
Footwear features calculation			
Footwear features calculation	20	4	-16
Last integrated design			
Starting last choosing	10	3	-7
Last design	40	20	-20
Foot-Last fitting	35	2	-33
Total time	**105**	**29**	**-76**

Using the KB system, the footwear design features calculation phase is now faster and more reliable. This activity can also be done by inexperienced technicians, since they are guided by knowledge within a database. Deploying this system starts a virtuous cycle because the knowledge grows as new shoes for new patients are designed. Using such a system increases the last design repeatability. Also the rate of non fitting shoe is reduced and more curative shoes are likely to be produced.
The starting last choosing phase provides a significant time saving advantage and allows the extracted last to fit the foot as well as possible.
The last designer software tool has been tested by one senior and one junior designer, both after a quick training session on using the software. The main advantage is given by the large time reduction, due to the specific commands for last modeling. Moreover, the amount of the modifications is precise since it is given by the KB system. Another interesting result, even if qualitative, is given by the possibility to delegate last design activities to junior designers, without losing the final last quality and process speed. Also design process repeatability is very high even if among different operators.

6. Conclusions

Literature overview shows that there is a need of dedicated systems to support the development of shoes for people with diabetes and there are no available effective technologies to overcome all problems implied in footwear customization. A general approach to manage shoe last development is defined. It sets the basis to innovate the process of customizing shoes for people with diabetes The paper is focused on the description of the adopted approach to define the design framework and on the results about the implementation of the design platform. The analysis of the results has highlighted:

- InfoHorma allows foot and relative last to be oriented by technicians using a protocol which goes beyond the simple geometric analysis. The procedure reflects the standard procedure manually used by the technicians;
- InfoHorma allows feet and shoe lasts to be measured according to a set of measures defined from the knowledge of experienced technicians. Using such a tool, time for foot/last fitting is dramatically reduced;
- Last designer is integrated with the measuring software, allowing the lasts to be rapidly modeled according to the foot pathologies. Very specific functionalities have been developed to design the last integrating the base commands provided by the CAD system.

The increasing need of integrated design tools leads to concentrate further research on the definition of outsole and insoles measurements and new concepts of foot/last/sole/insole fitting. For this reason, future research work is focused on the integration of tools for last, sole, insole and shoe upper design with foot/sole/insole/last fitting assessment tools.

Acknowledgement

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References

Bao, H. P., Soundar, P., Yang, T., Integrated approach to design and manufacture of shoe lasts for orthopaedic use, Computers & Industrial Engineering, Vol. 26, No. 2, pp. 411-421, 1994.

Boër, C. R., Dulio, S., Mass Customisation and Footwear: Myth, Salvation or Reality?, Spinger, 2007.

Boer, C., Dulio, S., Jovane, F., Shoe Design and Manufacturing, International Journal of Computer Integrated Manufacturing, Vol.17, Issue 7, pp 577-582, 2004.

Bogey, R., Gait Analysis, http://emedicine.medscape.com/article/320160-overview#showall.

Chau, T., "A review of analytical techniques for gait data. Part 2: neural network and wavelet methods", Gait & posture, Vol. 13, pp 102-20, 2001.

Cheng, F. T., Perng, D. B., A systematic approach for developing a foot size information system for shoe last design, International Journal of Industrial Ergonomics, Vol. 25, No. 2, pp 171–185, 1999

Davia, M., Germani, M., Mandolini, M., Mengoni, M., Montiel, E., Raffaeli, R., "Shoes Customization Design Tools for the Diabetic Foot", Computer-Aided Design & Applications, Vol. 8, No.5, pp 693-711, 2011.

Hutchins, S., Bowker, P., Geary, N., Richards, J., "The biomechanics and clinical efficacy of footwear adapted with rocker profiles", Evidence in the literature, Vol. 19, pp 165-170, 2009.

Leng, J., Du, R., A CAD Approach for designing customized shoe last, Computer Aided Design and Applications, Vol. 3, pp 377-384, 2006.

Luximon, A., Goonetilleke, R. S., Zhang, M., 3D foot shape generation from 2D information, Ergonomics, Vol. 48, No. 6, pp 625–641, 2005.

Luximon, A., Luximon, Y., Shoe-last design innovation for better shoe fitting, Computers in Industry, Vol. 60, No. 8, pp 621-628, 2009.

Raffaeli, R., Alfaro, D., Germani, M., Mandorli, F., Montiel, E., "Innovative Design Automation Technologies for Corrective Shoes Development", Proceedings of the 9th International Design Conference - DESIGN 2006,
Raffaeli, R., Germani, M., Advanced Computer Aided Technologies for Design Automation in Footwear Industry, IDMME-VIRTUAL CONCEPT 2008, 8-10 October 2008, Beijing - China, 2008.

Raffaeli, R., Germani, M., "Advanced Computer Aided Technologies for Design Automation in Footwear Industry", International Journal for Interactive Design and Manufacturing, Vol. 5, No.3, pp 137-149, 2009.

Redaelli, C., Sacco, M., Dulio, S., Boër, C., Analysis of cultural gap for customized products, 3rd Interdisciplinary World Congress on Mass Customisation and Personalization, MCPC 2005, 2005.

Sambhav, K., Tandon, P., Dhande, S. G., Computer Aided Design and Development of Customized Shoe Last, Computer-Aided Design & Applications, Vol. 8, No. 6 pp. 819-826, 2011

Smith, G., Claustre, T., A case study on concept design and CAD modelling in the footwear industry, International Design Conference, DESIGN 2006, Dubrovnik - Croatia, 2006. D. Marjanovic (Ed.), Dubrovnik, Croatia, Vol. 1, pp 315-322, 2006.

Xiong, S., Zhao, J., Jiang, Z., Dong, M., A., computer-aided design system for foot-feature-based shoe last customization, International Journal of Advanced Manufacturing Technology, Vol. 46, No. 1-4, DOI: 10.1007/s00170-009-2087-7, pp. 11-19, 2010.

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