Soles: Technology, Requirements, Testing

This article provides a total overview of soles, their function, tests to establish their suitability and safety, and the research projects currently being performed at PFI and ISC which are concerned primarily or partly with footwear soles.

Basic Function of Soles

Aside from considerations of fashion, soles – just like shoes themselves – have the primary task of protecting feet from unpleasant or even injurious environmental effects. As interface between the wearer and the ground, the sole is exposed to a wide range of physical and chemical actions, and has to:

- constantly resist the action of mechanical forces resulting from the weight of the wearer and the flexing action of the foot during walking
- protect the foot against injury, e.g., from sharp stones or other unpleasant features of the walking surface, and possibly against penetration by nails or the effects of chemicals
- protect the foot against heat, cold, and moisture
- assure slip resistance or grip on any possible surface
- depending upon the type of footwear, act as an electrical insulator or exhibit partial conductivity (work and safety footwear)
- depending upon the type of footwear and its intended use, it should support the performance of the wearer (sports shoes)

Soles should accomplish all these tasks without impairing the wearer's natural gait, and in such a way as to optimise or correct walking, running, and standing as compared to barefoot walking.

The ideal sole fulfills all protective functions, weighs hardly anything, is highly elastic, is dimensionally stable, allows the footwear designer a great degree of freedom, does not swell, is insoluble in chemicals, exhibits perfect adherence to the ground and zero wear, and lasts for ever. At the end of the footwear's life cycle, it can readily be removed from the shoe and be recycled. And not to be forgotten: The contribution of the sole to the overall price of the shoe should be as low as possible.

The list of requirements suggests that there is actually no such thing as a "miracle sole". However, some soles do exist which match the various demands and footwear types very well and even come very close to an ideal sole.

Manufacture

Function, material, structure, and production method of a sole and cannot be freely combined independently of one another. In the great majority of shoes produced globally, the upper and the sole are manufactured in separate processes and usually at different geographic locations. However, in some footwear, the sole and the upper are produced as an inseparable unit, such as in the case of polymer boots, swimming shoes, bathing sandals, or other plastic sandals, which can be produced as monomaterial products at low cost by injection moulding or meanwhile – more expensively but possibly individualised – by 3D printing.

Most soles are produced separately as individual shoe components and permanently bonded to the upper in an assembly step in the footwear factory. The commonest method of joining the two components is adhesive bonding. Certain types of shoe constructions, such as the flexible or the welt-sewn construction, require stitching. Leather soles are generally used in such cases because they can readily be replaced when they are worn. Custom-made shoes in particular often have stitched-on soles and can thus be readily resoled, which extends their useful lifetime and makes them more sustainable.

So-called direct soling offers an industrial alternative to adhesive bonding. In this method, the sole is injection moulded directly onto the finished upper. As for most tool-associated primary shaping processes, stable metal moulds are necessary. The considerable cost of the moulds has to be spread over the number of shoes produced.

Most soles are produced from polymeric materials by an injection moulding process. Yet not all sole geometries and structures can actually be produced by injection moulding. In the field of orthopaedic footwear, soles are fitted individually according to the shape of the foot and the medical finding. Accordingly, readily affordable machinable sole materials and techniques are employed, which generally precludes the production of individual injection moulds.

Thanks to technical advances in printing materials, individualised soles, soles having complex structures or textures, or soles with individually adapted damping zones can now be produced by 3D printing, although the choice of materials suitable for soles in constant use is still somewhat limited.

Fig. 1: Sole of a 3D-printed sports shoe produced in the ADDFactor EU Research Project in 2014 undergoing endurance testing on a PFI flexibility testing machine

Materials

Of crucial importance for the function, performance, and appearance of soles are the materials from which they are made. Owing to the differing physical properties, raw material costs, and ease of processing of the materials, soles are usually composites.

The bottom most layer of the sole, the actual outer sole, has to be particularly resistant to abrasion. Suitable materials are thermoplastic (injection mouldable) polyurethane material (TPU) or thermoplastic rubber (TPR) or vulcanised rubber, either synthetic rubber such as styrene-butadiene rubber (SBR), ethylene propylene diene monomer rubber (EPDM), or nitrile-butadiene rubber (NBR), if chemical resistance to fuels is required.

Other sole materials include leather, textiles, natural rubber / latex, cork composites, wood, and poly(vinyl chloride) (PVC).

A relationship exists between material density and abrasion resistance. The densities of outer soles are therefore relatively high. For example, SBR has a density of about 1.2 to 1.4 g/cm^3, NBR of about 1.2 to 1.4 g/cm^3. Outer soles are therefore kept relatively thin in order to save weight. The height of the sole is then made up of lighter, and also less costly, intermediate sole materials. These optimise the damping and comfort properties of the shoe and also the desired lift to be introduced. The material most commonly used for intermediate soles is polyurethane (PU, density about 0.3 to 0.6 g/cm^3) and the second most commonly used one is ethylene vinyl acetate (EVA, density about 0.9 g/cm^3), which is also suitable for the treading surface owing to its abrasion values. The good machining properties make EVA interesting for orthopaedic footwear. Light rubber (density 0.3 to 0.5 g/cm^3) is also used for this purpose.

Shoes with an adhesively bonded outer sole frequently have an insole made of leather, board, leather fibre material, or other composite materials.

The geometry of the bottom of a foot is defined by an insole – which is individually fitted in the case of orthopaedic footwear.

Any textile or leather cover sole which might be present is in direct contact with the sock or skin of the foot.

Sole manufacturers can influence the material properties and also the cost of soles via the injection moulding process and by the use of fillers.

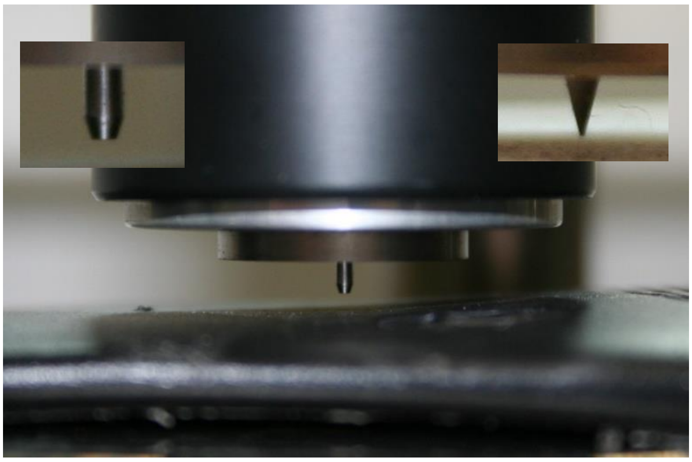


Fig. 2: Measurement of the Shore C hardness of an outer sole with an truncated conical indenter (upper left). Also shown is the indenter used for Shore D measurements (upper right).

In addition to the density, the hardness of the sole material is also an important parameter. The hardness of sole plastics is usually given in SHORE D (e.g. EVA 40, TPU 75). The determined hardness corresponds to the depth of indentation of a defined hard indenter on application of a given force. The indenter and depth of indentation vary according to the hardness scale. The hardness of injection-moulded parts – just like the density of plastics – is determined by the material, the injection moulding pressure, the temperature, and other factors.

It should be noted that the hardness describes a property measured at the surface of a body. The physical properties of a sole, such as its damping and stiffness, are determined above all by its structure and design. The overall stiffness of a shoe also depends upon the way in which the sole is attached to the shoe.

Quality

Like all other articles of daily use, footwear must also fulfill the expectations of the consumer. The sole should not become detached during the expected lifetime of the shoe. One of the objectives of quality control is to exclude such failures prior to the end of the expected lifetime. Reasons why a sole may no longer be suitable for use on a shoe are:

- damage arising from strain, such as a crack in the sole, breakage of the sole or a component such as the shank or protection against penetration
- through changes to the sole due to wear, such as sole abrasion
- premature ageing, for example due to a partly or completely detached sole because the adhesive bonding is not permanently stable or because hydrolysis has attacked the mid-sole

Possible reasons for failure of shoes and soles are examined on a daily basis in PFI's laboratories, almost always on new shoes before they are placed on the market. The task here is to reveal any shortcomings in the new state which could limit the expected useful life. In this way, deficiencies should also be identified which would preclude placing products on the market for legal reasons or make such action risky because they would increase the risk of complaints for the dealer or manufacturer. Reasons preventing placement of products on the market are the presence of hazardous substances in footwear or non-observance of standardised technical requirements, particularly in the field of Personal Protection Equipment (PPE).

A hundred thousand steps may be required of a shoe in the course of its useful life. Testing laboratories therefore examine not only the properties of shoes in the new state but also subject them to endurance testing. However, possible failures must be determined within days or even hours in the laboratory. In particular, when looking for information about wear it is necessary to significantly increase the physical load on the shoe and the sole above the levels of normal use in order to provide appropriate information within a short time frame. For example, an outer sole is intentionally damaged with multiple pricks or punctures prior to endurance testing. The evaluation criterion is then the extent of crack growth as a result of flexural loading in a standardised machine.

Penetration-resistant metal inserts, for example, are flexed one million times at a frequency of 16 Hz to establish whether they will break because of the flexing action of the foot during walking. Such high testing frequencies cannot be used for polymeric materials: they would warm up excessively and cast doubt on the meaningfulness of the tests.

One example which clearly illustrates the need for accelerated ageing tests in the laboratory will be familiar to many: A pair of shoes that that has long been kept unused in a cupboard feel perfectly good when put on the feet. However, walking feels strange and the intermediate sole of one or both shoes disintegrates before our very eyes. The reason is hydrolysis – destruction of the polymeric linking structures by the action of water vapour and heat – which may occur particularly in PU soles. Sole ageing is simulated in the laboratory by exposure to elevated temperature, humidity, and strong UV light.

Other typical deficiencies which are repeatedly observed at PFI and for which tests are specifically conducted are

- sole rupture
- detachment of sole from shoe
- detachment of heel
- heel breakage in shoes with a high heel lift
- shank breakage
- colour changes
- enhanced abrasion
- insufficient slip resistance
- insufficient water tightness

Additional deficiencies may occur and other tests may be necessary for safety footwear, such as

- insufficient protection against nail penetration / breakage of penetration resistant insert
- electrical conductivity too high or too low
- insufficient insulation against heat and cold
- insufficient energy absorption / shock absorption in the heel region

Important properties of soles in daily use are slip resistance and abrasion performance. They can be tested by various methods. The safety standard ISO 20344 tests slip resistance by a machine-based method which essentially determines a slip coefficient under defined conditions. For this purpose, the shoe to be tested is pressed with a defined force against a steel plate or tile possibly wetted with a lubricant and moved at constant velocity relative to the surface. The horizontal frictional forces are determined as an average coefficient of friction.

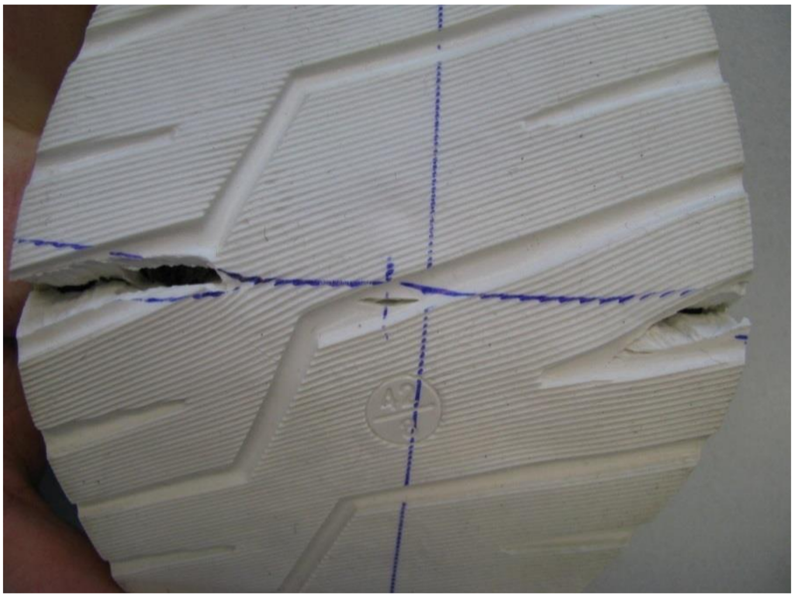


Fig. 3: Sole rupture after endurance bending testing in the PFI laboratory

The resistance to abrasion is ascertained according to DIN ISO 4649 by determining the mass of material abraded from a stationary cylindrical test specimen made of the sole material to be tested on movement over a sheet of sandpaper attached to a rotating cylindrical drum.

The effects of sole geometry and sole profile on abrasion and slip resistance were investigated in a PFI research project and the results used to develop design guidelines. An in-house constructed contact surface measuring device was used to establish the influence of contact surfaces and profile edges as well as compression effects during the slipping process.

The leading profile edges are especially important on a wet surface (windscreen wiper effect). Subsequent light grinding down of sharp edges led to significantly lower coefficients of friction. The effect of profile shape, surface hardness, microstructure of the surfaces and contact surfaces could be studied with the aid of a sole which produced by a kind of building block approached. Small contact surfaces gave better coefficients of friction but greater abrasion because of higher pressures.

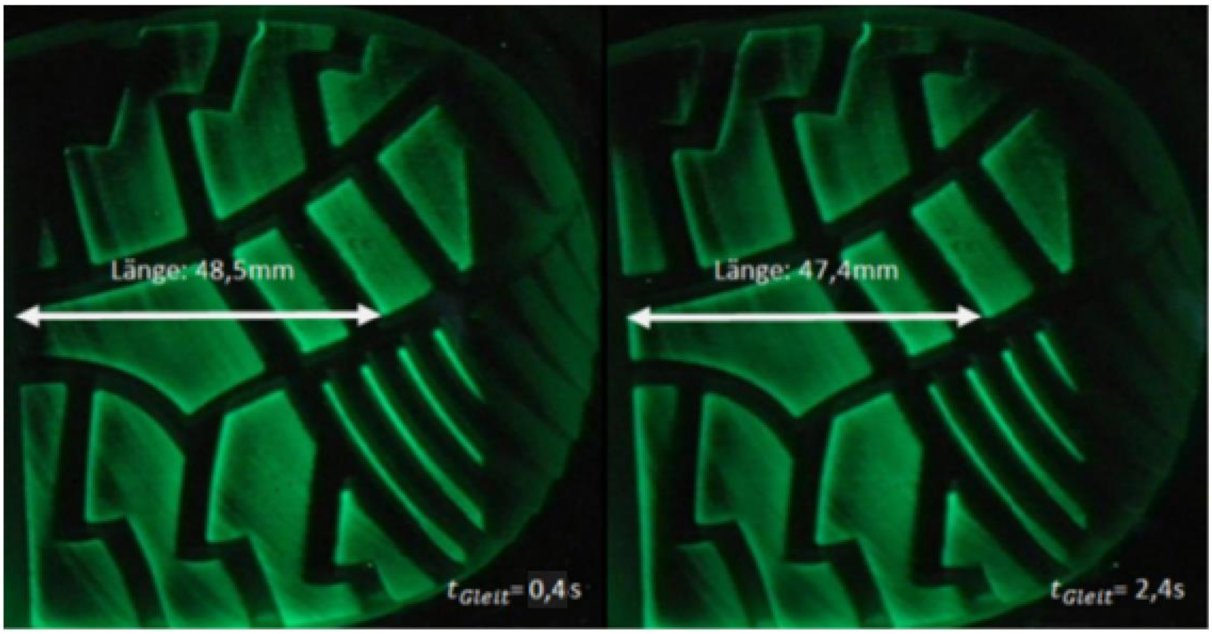


Fig. 4: Image of the contact surface of a sole at the beginning and in the middle of the slipping process on a PFI slip resistance testing machine. From the AiF 1761N Research Project – Sole Construction Guidelines with Regard to Optimised Slip Resistance and Breaking Strength.

Prevention of Toe Caps Sinking into the Sole

Fig. 5: Descent of toe caps into the sole with increasing force on being run over (Concluding report of AiF Project 17636)

An essential requirement of safety shoes is that they provide protection of the toes against falling objects or heavy weights, as described in ISO 20345. Understandably, this requirement concerns the toe caps themselves. ISO 20344 describes a drop test in which the distortion of the shoe in the forefoot region has to be limited during the entire period of load application. A plasticine cylinder placed in the shoe interior in the toe cap records the actual distortion of the cap even if the cap recovers completely or partly after application of the load.

It is less obvious at first glance that the sole has to make a significant contribution to protection of the forefoot

Even though classical toe caps provide good protection against injury by heavy objects which fall onto the forefoot region, there is a lack of protection if the foot is run over.

In a research project, PFI investigated the behaviour of protective toe caps when a fork-lift truck runs over the forefoot. It was seen that the toe caps may be pressed far into the sole or even into the ground together with the sole – with fatal consequences for the forefoot of the wearer, who will experience the opposing force acting from below via the sole and suffer injury and possibly crushing. The material and construction of the sole and in particular the method of attachment of the caps are relevant here.

Fig. 6: Compression test according to ISO 20344 – here 5 kN

Tests according to ISO 20344 also clearly illustrate the difference between testing with a drop hammer (which simulates the falling of a heavy object) with a predetermined energy (100 J or 200 J) and testing with a pressure die (which simulates running over) with a pre-set force (10 kN or 15 kN). In the drop hammer test the kinetic energy of the falling mass is dynamically transformed into deformation work. This deformation work gives rise to permanent deformation, heat, and a small recoil. Ultimately, the energy has to be used somewhere: In the toe cap, in the sole or – hopefully not – in the plasticine cylinder (the foot), even though the protective toe cap may be infinitely stiff. In the compression test no energy is transformed if the shoe construction is infinitely stiff because no (deformation) work is performed. However, shoes are not infinitely stiff, this applies particularly to soles in comparison to toe caps, so that the compression forces effect a penetration of the toes caps because of the finite stiffness of the sole, introducing energy into the sole which ultimately is partly returned to the muscoskeletal system, remains in the sole as heat, or causes permanent deformation (ruptures) in the sole.

Protection Against Penetration by Sharp Objects

In addition to protection of the foot from above, safety shoes have to protect feet from penetration of sharp objects – such as nails – through the sole from below. This is also described in ISO 20345 and is tested in the so-called nail-penetration test: Nails of defined geometry are slowly driven into a sole at four or five different places (at a rate of 10 mm/min). Depending upon the material used for protection against penetration and the nail, maximum force, which is always greater than 1.1 kN, or a predetermined force (1.1 kN) is applied, without the tip of a nail penetrating the sole (becoming visible).

Electrical Resistance

The electrical resistance of a sole describes the current which flows when a potential difference exists between the body of the wearer and the ground. A current of just a few milliamperes can be dangerous for humans. Therefore, the electrical resistance of shoes should be a great as possible to provide protection against electric shocks, for example during electrical work. On the other hand, a high resistance of the soles increases the likelihood of electrostatic charging. In the interest of reducing electrostatic charge to protect electrostatically sensitive components (ESD) the electrical resistance should be low. Realistic values lie in the range of 10 MΩ (10^7 ohm) to 10 GΩ (10^{10} ohm). Friction between floor covering and shoe sole is always involved in electrostatic charging.

In a current research project, PFI, the German Carpet Research Institute, Aachen, and the Dresden Institute for Wood Technology are jointly investigating the possibility of making the electrostatic charging properties of floor coverings testable.

Performance

Orthopaedic footwear technology is concerned with the functionalisation and adaptation of a shoe to the needs and requirements of the wearer by way of soles and insoles. This often results in complex individualised shoe bottoms.

However, much effort is also invested in sole design for non-orthopaedic footwear. The desire for high performance of products of attractive, fashionable design and various legal requirements in the area of safety shoes have led to the development of a sophisticated array of soles meeting high demands regarding both the materials used and design.

In particular, manufacturers of sports shoes are engaged in a process of permanent innovation of soles to make their shoes lighter and to increase the effectiveness of damping in order to return energy expended in the propulsion phase to the wearer on making contact and to adapt the traction to the requirements of the pertinent activity on accelerating and decelerating. Thus, every kind of sport has its specific shoe type. There is a corresponding degree of variety in the range of possible sole constructions.

In addition to testing for recognisable defects, there are other measurable properties of soles which affect the comfort, functionality, and performance of shoes. Examples are:

- weight of the sole
- thickness of the sole
- damping properties (especially in the heel region)
- hardness of the sole surface
- flexibility of the sole
- fit-relevant parameters (such as shoe length, width, sole design dimensions)
- climatic parameters (such as thermal insulation, heat capacity)
- water tightness

Low weight is a property of a shoe which features much in advertising and in which considerable development work is invested. A rough calculation shows that even small shoe weight savings of a few grams can lead to measurable improvements in high-performance sports at high speeds and high stride frequencies.

The damping properties of a sole can be measured by static and dynamic methods. It is justifiable to question whether a test for energy absorption performed with a pressure die moving at a speed of 10 mm/min (as in the test for energy absorption in the heel region for safety shoes to prevent fractures of the heel bone) is suitable as a basis for statements about performance. Tests in which the energy absorption and force distributions of a drop test are recorded are more meaningful.

Fig. 7 shows the force path during application of a heel-shaped metal test piece on the heel region of a sole over the depth of penetration and, for the sake of comparison, the result obtained with a linear spring, both measurements being performed on a PFI shock absorption testing machine.

The area between the s-axis (path) and the red curve (force) represents the energy imparted to the heel by the falling mass. The area between the s-axis and the green curve is the energy which is retuned by the sole. Accordingly, the area surrounded by the red and the green curve is the energy absorbed by the sole – and converted into heat. The black inside curves represent the second and third impact until a point determined by the weight of the falling mass and the stiffness of the sole.

In the case of the linear spring it is seen that almost no energy is absorbed and a correspondingly high number of further impacts on the spring take place. The slope of the curve corresponds to the spring constant from Hooke's law, first encountered during physics lessons.

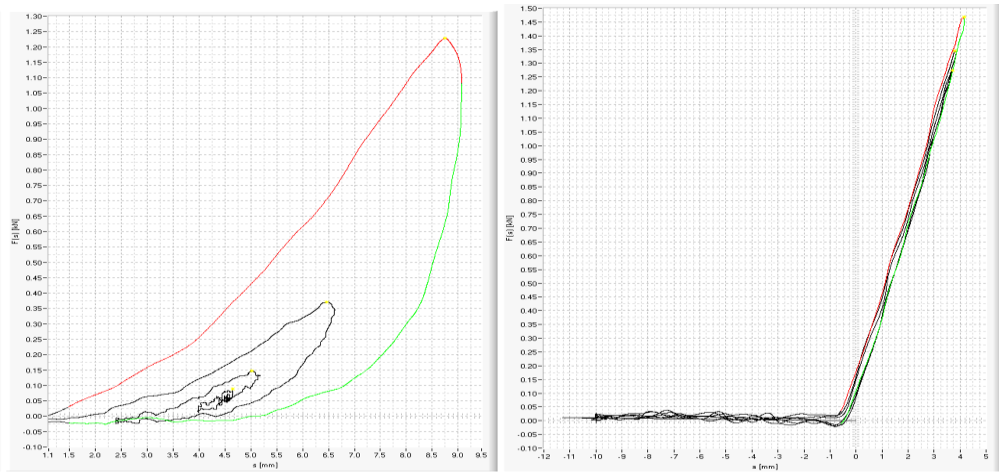


Fig. 7: Typical force-path diagram of a shock-absorption measurement in the heel region of shoe sole and for comparison that of a linear metal cylinder spring

Since part of the kinetic energy is converted into heat on passive damping in soles, the question arises whether this energy could not be used in another way. The expected energy converted into heat per stride by a person weighing 70 kg on landing on his heel and compressing the sole by 5 mm is estimated as

$W_{step} = m * g * h = 70 \text{ kg} * 9.81 \text{ m/s}^2 * 0.005\text{m} = 3.4 \text{ J}$

At a step frequency of f = 1 Hz (walking) this yields an output of $P = ½ f * W_{step} = 1.7$ W per shoe. Assuming a very good efficiency of an electrical generator of this order of magnitude, a maximum power output of 1 watt can be generated in a shoe on walking with active damping in the heel region.

In a research project undertaken together with HSG-IMIT (Institute of Micro- and Information Technology of the Hahn-Schickard Society), PFI has developed electronic components for the generation and storage of electrical energy derived from movement, so-called energy harvesters, which extract unused energy from systems of the environment and utilise it for sensory applications. In another project, PFI has developed a system which generates electricity by the dynamo-electric principle during the flexural heel to ball motion of the foot. This electricity is then used to climatise the shoe through an actively ventilated sole. The practical benefit of this generator is that electrical energy can be generated on walking and used to drive the sensory applications in the shoe constantly without any need for exchange or recharging of batteries.

With regard to the use of sensors in shoes, the PFI subsidiary ISC (International Shoe Competence Center) and PFI have collaborated in a research project to develop a new sensor-based shoe in which a measuring system for gait analysis and training monitoring is totally integrated. This shoe could support out-patient rehabilitation of injuries or diseases which affect human gait and be of valuable service in therapeutic documentation and objectification of therapy and its progress.

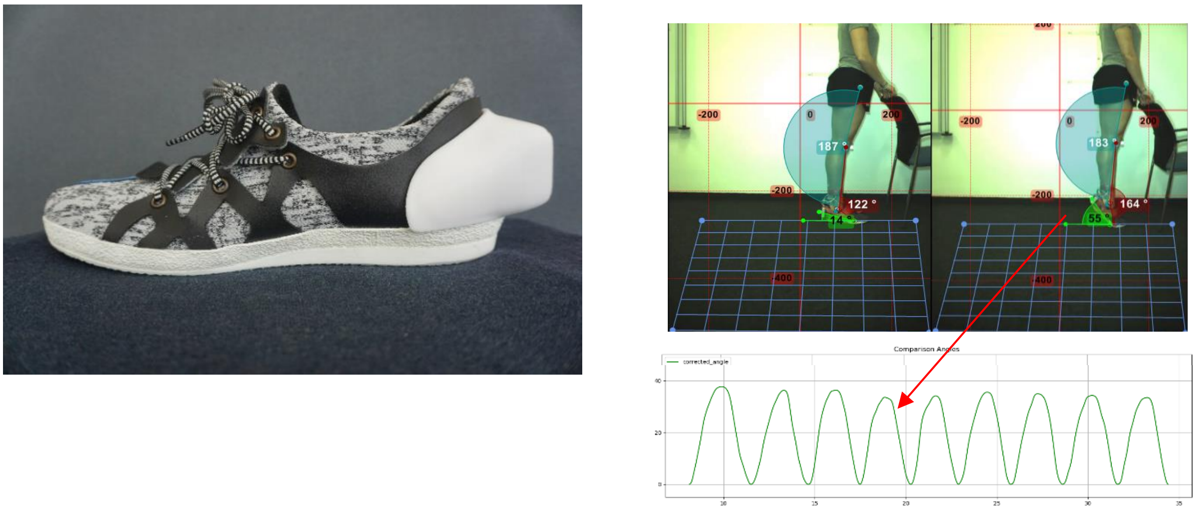


Fig. 8: Shoe with measuring system developed by ISC and PFI in the "Sensor-based Rehab Shoe" Research Project

All the protective functions that a shoe can offer exert an influence on the biomechanics and gait of the wearer. Stated rather crudely, the greater the protection and the decoupling from the environment, the more the gait will differ from barefoot walking. One important measurable criterion is flexibility in torsion and flexing (rolling over) of the shoe which is determined primarily by the sole. The flexibility of shoes and soles can be assessed quasi-statically and dynamically by a testing machine. This was investigated in a research project and various studies performed at PFI. Interestingly, it was found that most shoes – as expected – were less stiff after several loading cycles and asymptotically approached a constant value. However, after a recovery time and re-examination they again exhibited a stiffness close to the initial value.

It would be of advantage if the sole stiffness and damping could be adaptively adjusted to various wearing situations. In the research project "Smart Shoe Comfort – Development of Smart Interior

Bottom Components for Situation-Determined Comfort Adjustment of Shoes", PFI together with Kaiserslautern University and ISC developed technical possibilities for achieving this aim.

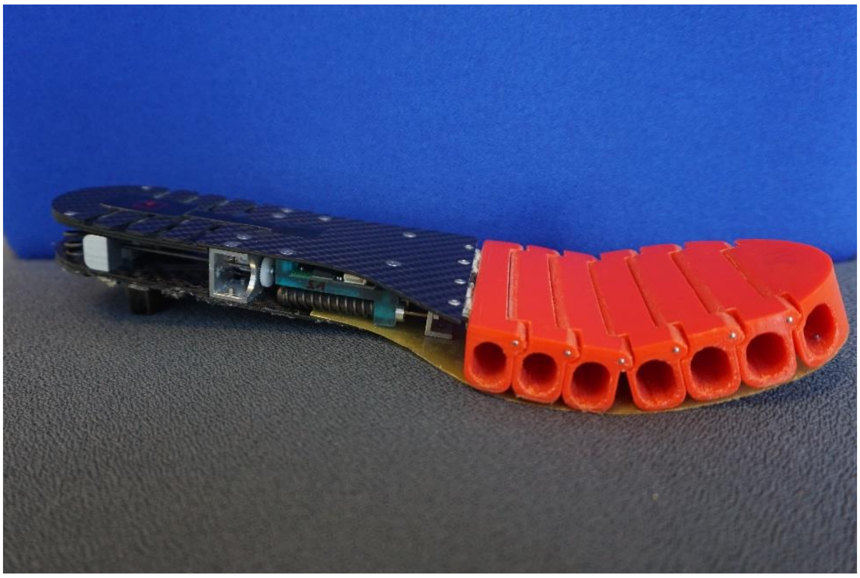
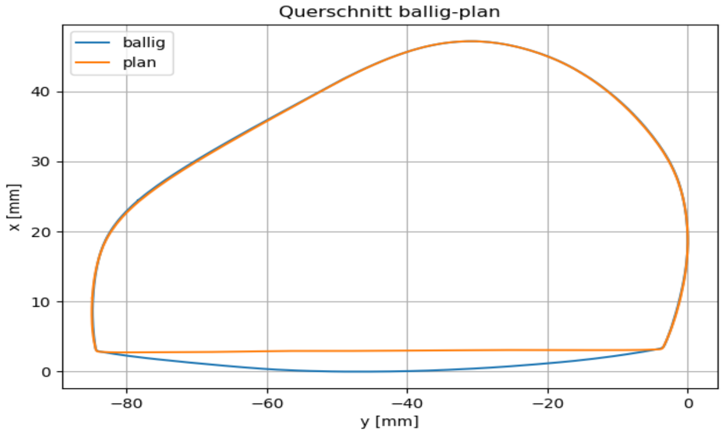


Fig. 9: Example of a sole with adjustable stiffness. From the AiF Research Project "Smart Shoe Comfort" undertaken by FH KL, ISC, and PFI

Another study undertaken at ISC and PFI was concerned with the question of the optimum cross section of the foot bed in the metatarsal region of safety shoes. Shoes currently exhibit a convex sole shape and that point, meaning that the third metatarsal lies lower than the first and the fifth. It was examined whether a flat cross-sectional profile would possibly correspond better to the biomechanical requirements in the shoe, and appropriate solutions were developed for implementation thereof without incurring disadvantages for the foot volume in the shoe.



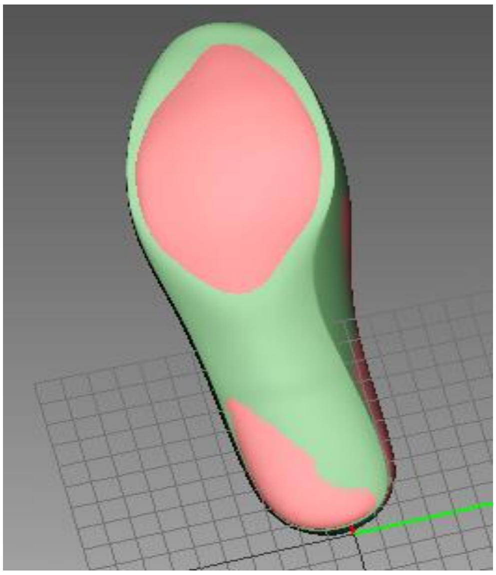


Fig. 10: Adapted forefoot geometry of the sole of an innovative last. ISC Research Project

Recycling

It was mentioned at the beginning of this article that soles exist which can be replaced for repair purposes. Unfortunately, this is not the case for 99 percent of the shoes currently in use. Sole attachment is generally not a reversible process. If soles can be detached, this is usually an undesired phenomenon. Recycling of footwear receives only marginal attention in present-day footwear design and production processes.

For PFI “Shoe Recycling” is a constant area of research. The possibilities of shoe composting or the use of renewable raw materials, especially biopolymers, are examples of the topics studied. As the dominant component with regard to both mass and volume, the sole attracts particular interest. Since the obligation to provide recycling concepts will very soon apply to the footwear industry, PFI is currently developing a pertinent research project.

Please address any questions to:

Dipl.-Ing. Peter Schultheis
Head of Technical Development and Footwear Technology
Tel.: +49-(0)6331–249040
E-Mail: peter.schultheis@pfi-germany.de