Novel Approach for a Hybrid Cushioning System in Running Shoes based on Halbach Arrays

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Abstract: A novel design approach making use of purely elastic magnet modules based on Halbach arrays for hybrid midsole constructions is proposed. Recovery of the surrounding midsole material after compression may thus be supported. In order to overcome challenges induced by the properties of ferromagnetic materials specific design principles had to be developed and implemented. In particular, mechanical guidance of the magnetic elements in vertical direction had to be ensured. FEM simulation has been applied in order to identify practicable geometrical arrangements of the magnets. Sufficient guiding accuracy was achieved by developing an effective structure utilizing dual Halbach arrays pivoted at a flat angle to one another using a common axis of rotation. Prototypes of midsoles and running shoes which utilize the novel technique have been manufactured. Validation tests revealed significantly higher stiffness of the modified midsoles and a reduced spring deflection. Biomechanical tests of the modified running shoes are in progress.

1 INTRODUCTION

The use of foamed polymer materials in the midsoles of running shoes (e.g., EVA, PU) has developed over decades and, with the introduction of thermoplastic polyurethane (TPU), has led to a noticeable increase of performance in terms of rebound properties while reducing mass at the same time. The combination of cushioning (viscous) and spring like characteristics (elastic) make these materials the first choice. The naturally high impact forces during a heel strike foot pattern put enormous strain into the cell structure of midsole materials and inevitably lead to material fatigue (Chambon et al., 2014). Practical tests show that selected mechanical parameters such as the energy return change after just a few hundred kilometres. With increasing use of running shoes, an increase in the peak forces that occur during impact (Baltich et al., 2015) can therefore be seen more frequently, which is associated with a higher risk of potential joint damage or other disadvantages regarding the musculoskeletal system (Agresta et al., 2022). In this paper, we propose an unconventional design approach in the form of a purely elastic magnet module for hybrid midsole constructions, which among other aspects has the potential to support the recovery of the surrounding midsole material after compression. Furthermore, we hypothesize that the progressive behavior of the repelling magnets might interact with the sensorimotor/postural control mechanism, which in turn might result in higher pre-activation of the neuromuscular system. All in all, this approach could help to extend the lifespan of a running shoe and at the same time to provoke a more active foot strike technique in running, in which muscular structures take over part of the cushioning and thus partially reduce the stress on the involved joints.

Based on the accumulated experience we share some insights into the entire development process, starting with rudimentary considerations about the design, followed by simulation-based constructions and handmade prototypes and concluding with first biomechanical tests in running shoes under laboratory conditions. The idea for this specific approach came from a long-standing project partner (Grell M., inventor), who was scientifically supported by the Department of Biomechanics (Section Sports Technology) of the Institute of Sports Science at the University of Vienna. The developed technology is

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already protected by patents. Alternative use cases other than running shoes are currently discussed.

2 WHY MAGNETS?

The forces acting on the shoe during running as well as the high number of load cycles put a strain on the underlying construction which usually lead to varying degrees of material fatigue over the long term. In order to reduce this undesired effect somewhat, we resorted to the principle of repelling magnets (high graded neodymium) in our approach. When two permanent magnets with the same polarity come together, opposite forces (repelling forces) with progressive spring characteristics are generated. The compression phase takes place without any physical contact between the two elements (air gap) and thus enables an enormously high number of cycles without any noticeable weakening of the elastic properties compared to foam materials.

2.1 Halbach Arrays

A special arrangement of single dipole magnets in a predefined sequence (the so called “Halbach array”; Halbach, 1980) enables the usually symmetrical formation of the magnetic field to be extensively shifted, resulting in an asymmetric dipole with a stronger and a weaker side (Figure 1). The individual

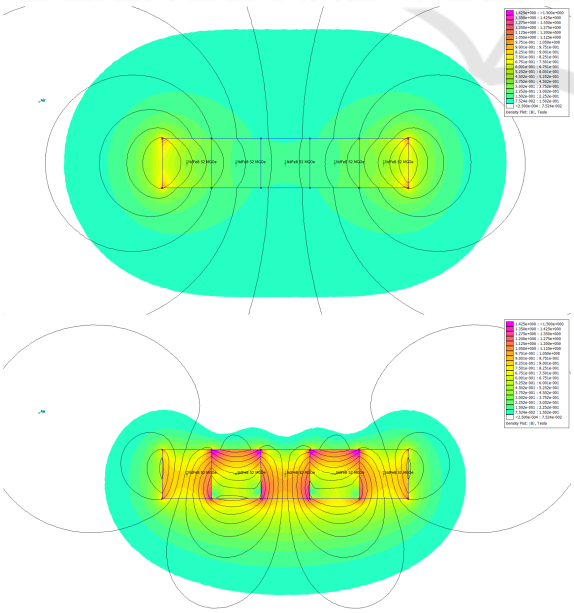

Figure 1: Example of magnetic field distributions for uniaxial aligned magnets vs a Halbach array (FEMM 4.2).

magnets are aligned with each other in alternating orientation (e.g. 5 segments in 0 | 90 | 180 | 270 | 0 deg. of angular direction) and combined to form an array.

The combination of two such arrays aligned on their stronger sides in one construction enables an enormous increase in the resulting repulsion forces. Similarly, the Halbach array structure allows a reduction in the materials used with the same effect in terms of repulsive forces. In principle, the desired spring curve can be specifically adjusted by varying certain construction parameters (number of magnets, dimensions, geometry) and adapted to individual needs (customized technology).

2.2 Challenges

In addition to positive aspects such as increased service life (no fatigue effects) or faster rebound (no damping), this approach also entails additional challenges. Ferromagnetic materials have a much higher density compared to foamed materials (about 7.5 g/cm³ vs. 0.25 g/cm³) and would significantly increase the total mass of a running shoe even with low material usage. Therefore, a possible use should be locally limited and in any case be in functional coordination with the entire running shoe. The spatial conditions in the area of the midsole needs also to be considered (shape and maximum height).

From a design point of view, one of the most important aspects when using magnets is to ensure mechanical guidance in the vertical direction when two magnets approach each other. Without this, an unwanted lateral evasive movement would immediately occur, reducing the intensity of the repulsive forces. When using Halbach arrays, there is also the risk that shifts beyond a segment width will result in a reversal of the effect (instead of a repulsive effect, both arrays will strongly be attracted).

2.3 FEM-Simulation

In order to be able to better estimate the influence of different geometry, arrangement (iteration step size) and number of segments on the repulsion effect, numerous simulations were carried out with a free simulation software (FEMM 4.2). The specific material characteristics (required for the simulation of the magnetic fields) could be obtained from various data sheets from manufacturers and distributors (K&J Magnetics). Specifically, a simulated compression of two arrays with an assumed air gap (10 mm) up to complete contact (0 mm) was calculated. In addition to the respective formation of the magnetic fields, the results also provided the resulting vertical forces at a certain distance (air gap). In this way, spring characteristics of different variants could be compared and an optimized version identified with regard to their effect in combination with the respective mass (Figure 2a).

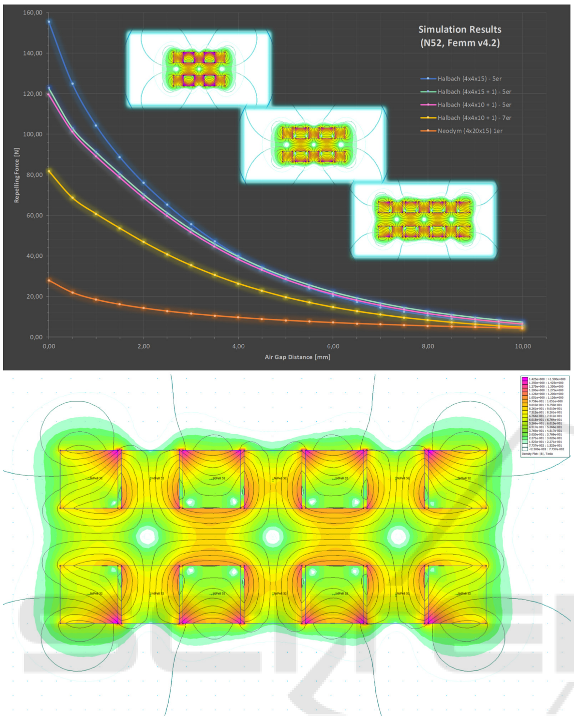

Figure 2: (a) Simulation results of different Halbach array variants (force vs. distance). (b) Interaction between two Halbach arrays of the final version (7 segments).

The finally selected magnet had a cuboid geometry with the dimensions 4x4x10 mm (height x width x depth) and consisted of an N52 graded neodymium material with a nickel coating. For a single Halbach array, a total of 7 segments have been combined in an alternating sequence with an offset angle of 90 degrees each. In any case, the individual segments have to be fixed in their position, since the naturally developed magnetic flux of a dipole would lead to displacements under the magnets. This can basically be accomplished by gluing into a template or by press fitting into a predetermined fixture.

3 DESIGN, CONSTRUCTION AND MANUFACTURING

At the beginning of the project, numerous preliminary considerations, sketches and test setups were made for possible arrangements of two Halbach arrays and for the selection of materials. The most challenging was the low overall height (assumption: max. 15mm) as well as the realization of the necessary guidance accuracy (assumption: horizontal deviation <10%). This challenge can be overcome either through form-fitting connections of the surfaces involved (e.g. two components sliding into each other) or with or with the help of vertical guide rails and tilt-resistant guide bushes.

When two components are connected in a form-fitting manner, displacements inevitably lead to friction losses on the contact surfaces. As a consequence of the high number of repetitions to be expected, there is also unwanted material abrasion as a sign of wear. On closer inspection, the second idea also did not appear to be entirely practical, as it could be prone to tilting during compression and rebound. As an alternative, another possibility was therefore developed in which the two arrays can be pivoted at a flat angle to one another using a common axis of rotation (e.g. hinge joint). In order to improve the effectiveness, the idea of a mirrored structure was born in which two double arrays work together (see Figure 3).

Figure 3: Final draft for the design of the magnetic module with dual Halbach arrays (frontal & perspective view).

This variant is less sensitive to decentralized force application (COP) and, according to the simulation, achieves a maximum repulsive force of about 230 N (fully compressed, air gap = 0 mm) with a total mass of less than 50 g. In coordination with the surrounding material and due to the limited installation height, a design-related preload of 50 N was implemented with a remaining deflection of almost 6 mm.

The complete implementation was carried out using a commercially available CAD program (SOLIDWORKS®). Additional FEM simulations have been conducted to obtain the necessary material specifications. The high material requirements in terms of rigidity and strength led us to opt for a highly rigid carbon fiber reinforced plastic (20% CF filament). During construction, attention was paid to the compatibility of the components with regard to 3D printing and the accuracy class of our production options (minimum layer thickness 100 µm). Spring steel with a diameter of 1.5mm was selected as the common axis, and the individual elements for holding the magnets were produced using a 3D FDM printing process (Ultimaker S5 Pro Bundle).

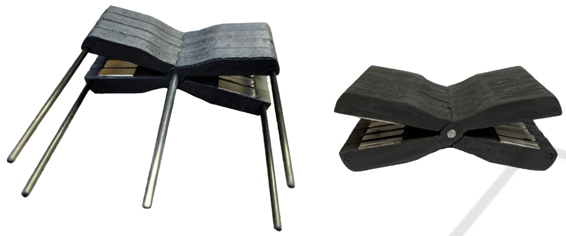

Figure 4: (a) Manual assembly (b) one finished module.

The assembly was done by hand and the individual segments were glued together with cyanoacrylate (superglue). The individual elements were fitted with the magnets and then strung in the specified order on the common axis of rotation and also on stabilizing carbon rods at the outer ends (Figure 4). The manufactured module was subjected to simple function tests (application of mechanical loads) and series of measurements were carried out using a force measuring platform, which substantiated the simulation results (spring characteristics).

4 VALIDATION

4.1 Artificial Tests

As mentioned in the introduction, the innovative magnet module is to be used specifically in combination with surrounding midsole materials. For functional tests, a test specimen (e.g. made of foamed EVA) with a suitable mount for a module is required. To produce this, cuboids were cut out (70 x 70 mm, 20 mm thick) and the negative form of a complete module was milled using a CNC milling machine (Figure 5). The specimen was designed to be subjected to dynamic tests on a professional hydraulic test stand with standardized stamps (imitation of the human heel geometry). In this case, cyclically repetitive impact movements are carried out at a defined ingress/egress speed and the reaction force acting on the contact surface is measured.

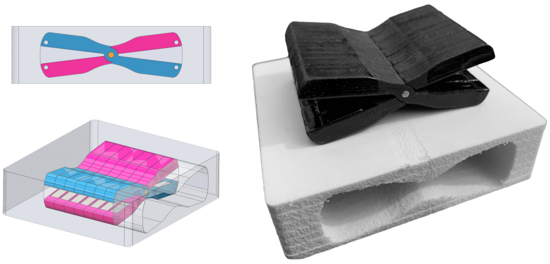

Figure 5: Specimens for test trials.

The midsole materials used in running shoes are usually tested on the basis of such test series and examined with regard to rebound, cushioning and material fatigue (Schwanitz et al., 2010).

Within an international cooperation, we were able to have some test series performed with the previously mentioned test stand in order to make a direct comparison between the hybrid variant and the unmodified material. 1000 cycles at a frequency of 1.4 Hz (corresponds to a simulated running speed of about 10 km/h) with a maximum vertical force of 1000 N were applied to the respective test specimen. In the results, we concentrated on cycle #100 (material warm-up) and #1000 (first material fatigue) and calculated, among other, parameters for assessing energy loss and stiffness (Figure 6).

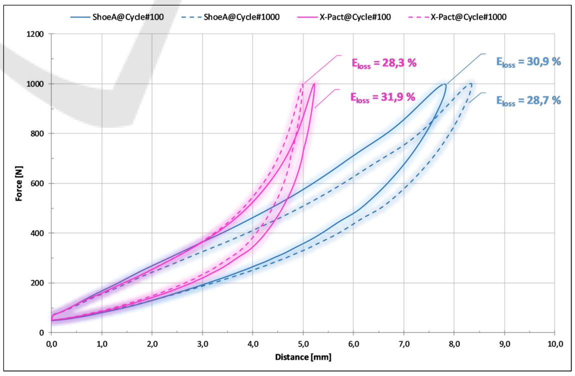

Figure 6: Test results (hysteresis) for the hybrid-specimen and unmodified EVA material for cycle #100 and #1000. The unmodified variant shows the first signs of material fatigue (reduction in stiffness, increased energy loss) after just 1000 cycles, while the hybrid version remains very stable in this respect.

As can be seen quite clearly, the progressive spring characteristic of the magnet module has a strong influence on the overall structure (test specimen + module). In a direct comparison, the new approach shows a significantly higher stiffness, but in combination with a reduced spring deflection (due to the incompressible elements). Based on the changes over time after 1000 cycles, the results in terms of energy return are on a similar level. Surprisingly, there is a slight trend towards more rigidity in the hybrid construction, while the EVA material loses a little in rigidity.

4.2 Biomechanical Tests

A first pilot study to evaluate the possible effects of a magnetic module in a conventional running shoe is currently being carried out. A pair of running shoes was modified in such a way that the midsole material was separated between the heel bone and the longitudinal arch to accommodate one module each (Figure 7). The second pair of running shoes remained unchanged. Subjects participating in our experiment are asked to run with both variants after a few minutes of warm-up, at a controlled running speed (endurance pace) over force measuring plates mounted into the ground. In addition to the ground reaction forces, we record EMG data in selected muscle groups of the lower extremities.

The aim of this pilot is to identify possible interaction effects both in terms of dynamics and neuromuscular activation and to observe individual responses (responders vs. non-responders).

Figure 7: Modified prototype of one selected model of running shoes for biomechanical performance tests and comparison to unmodified version.

5 CONCLUSIONS

Using the latest construction methods (FEM simulation, CAD design, rapid prototyping), a new type of magnetic spring suitable for running shoes has been developed and manufactured. The thereby created novel module was compared and evaluated in several test series and confirmed our expectations. A pilot study currently being carried out focuses on the practical suitability for use in common running shoes. We expect further results on efficiency, design issues and acceptance, which might also help in transferring the magnetic technology to other areas than running.

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