Using topology optimisation to generate personalised athletic footwear midsoles

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Abstract: A number studies have shown that adding mass to a runner's footwear increases oxygen uptake (e.g. Frederick, 1983) and thus the metabolic cost of running. However, further studies have also suggested that shod running may provide an energetic advantage over a barefoot condition for habitual rearfoot runners (e.g. Kerdok et al., 2002). As a result of these findings, lightweight performance footwear that still offers some degree of cushioning represents a large segment of the running shoe market (Nigg, 2009; Asplund & Brown, 2005).

A finite element footstrike model was developed and used with the Abaqus Topology Optimisation Module (ATOM) to output lightweight athletic footwear midsoles optimised for an individual athlete's personal loading profile. Biomechanical running trials were performed by three healthy, male subjects (two rearfoot strikers, one forefoot striker) such that triaxial ground reaction forces and plantar pressure distributions could be measured. These loads were then applied to a generic midsole geometry via 20 rigid plates representing the plantar surface of the foot. An optimised midsole geometry for each subject's loading profile was subsequently generated with the objective function of each analysis being to minimise strain energy whilst simultaneously satisfy a constraint defined to ensure the midsole volume remained below a certain threshold.

As expected, each of the midsole geometries output retained material at areas of higher loading whilst material savings were made in areas experiencing lower levels of loading. This resulted in a distinct solution for each subject's individual load profile. Geometric restrictions were also applied in subsequent analyses.

Keywords: Topology Optimisation, Athletic Footwear, Running.

1. Introduction

Mass customisation is the concept of "producing goods and services to meet individual customer's needs with near mass production efficiency" (Tseng & Jiao, 2001) and was embraced relatively early by the footwear industry (Piller et al., 2012). Whilst brands have offered customers the ability to customise both the fit and aesthetic design of their footwear, with the exception of Shimoyama et al. (2011), little opportunity exists to similarly optimise footwear function (Pandremenos et al., 2010).

First reported by Frederick et al. (1983), a number studies have shown that adding mass to a runner's shoes increases submaximal oxygen uptake by approximately 1 % per 100 g per shoe. However, further studies have also suggested that shod running may provide an energetic advantage over a barefoot condition for habitual rearfoot runners (e.g. Kerdok et al. 2002). This suggests that the advantages of shoe cushioning may counteract the negative effects of the added mass (Franz et al. 2012). As a result of these findings, lightweight performance footwear that still offers some degree of cushioning represents a large segment of the running shoe market (Nigg 2009; Asplund & Brown 2005).

Lieberman et al. have conducted a significant number of studies into different running footstrike styles and concluded (2010) that "…runners who forefoot or midfoot strike do not need shoes with elevated cushioned heels to cope with [the] sudden, high transient forces that occur when you land on the ground." This suggests that footwear could be optimised to a runner's individual footstrike pattern, only providing support under the areas of the foot that are highly loaded, with material omitted elsewhere. This could potentially result in the associated energetic advantages of a lightweight footwear design whilst still providing cushioning where required.

The primary role of the midsole is to cushion the foot and attenuate footstrike loading (Chase, 2009). It is also typically the heaviest component of an athletic shoe so has the greatest scope for optimisation. Based on the "Material Distribution Method" (Bendsøe & Sigmund 2003), this paper details the use of the Abaqus Topology Optimisation Module (ATOM) to output lightweight footwear midsole geometries optimised for an individual subject's personal footstrike loading profile. Crucially, all boundary conditions were determined from biomechanical running trials to ensure that loading representative of a real running footstrike was applied.

2. Methods

2.1 Biomechanical testing

Biomechanical running trials were performed by three healthy, male subjects (two habitual rearfoot strikers, one habitual forefoot striker) whilst wearing a pair of basic athletic shoes provided by the study's industrial sponsor. Each shoe consisted of an ethylene-vinyl acetate (EVA) midsole, a blown rubber outsole, a simple laced upper and was fitted with a standard foam sockliner. All participants gave informed ethical consent to take part in the study which was conducted in accordance with the protocol approved by the Loughborough University Ethical

Advisory Committee. The two rearfoot strikers will be referred to as Subject A and Subject B throughout this report whilst the forefoot striker will be referred to as Subject C.

The vertical, anteroposterior and mediolateral components of the ground reaction force (GRF) applied during each trial were obtained with a piezoelectric analogue force platform (Kistler, Switzerland) whilst the distribution of plantar pressure was recorded using an in-shoe capacitive pressure sensor (Novel, Germany). A multi-output transistor-transistor logic (TTL) trigger ensured that the activation of both systems occurred simultaneously with a sample frequency of 100 Hz selected. Reflective laser timing gates were used to monitor running speed which was controlled to be 4.0 ± 0.1 ms^{-1}.

The plantar surface of the foot was segmented into 20 discrete regions with the triaxial loads exerted on each sub-area of the foot estimated by combining the data output by the force platform and pressure insole. This approach has been employed in a number of reported studies on human gait (e.g. Abuzzahab et al. 1997; Giacomozzi & Macellari 1997; MacWilliams et al. 2003; Saraswat et al. 2010) and is based on an "assumption of proportionality" between the global GRF components measured by the force platform and the local distribution of plantar pressure as recorded simultaneously by the pressure insole. This approach allowed triaxial load amplitudes to be determined for each of the 20 defined sub-areas of the foot.

2.2 Finite element modelling

2.2.1 Base model

A generic midsole geometry was created, meshed with linear hexahedral elements and assigned an isotropic linear elastic material model. Material properties were determined from appropriate mechanical trials. The 20 sub-sections of the foot's plantar surface were represented by rigid plates with the maximum 3-D load predicted to occur in each region identified from the biomechanical analysis discussed in Section 2.1 and applied to the respective plate using a ramp amplitude. Each rigid plate was tied to the top surface of the midsole whilst the nodes on the bottom surface of the midsole was also constrained in all spatial degrees of freedom.

This approach minimised the solve time for each individual analysis, something that is particularly important when developing a model for optimisation as the base analysis is run many times in succession. ATOM is only compatible with Abaqus/Standard so each analysis was submitted to the implicit solver. The complete base model is shown in Figure 1.

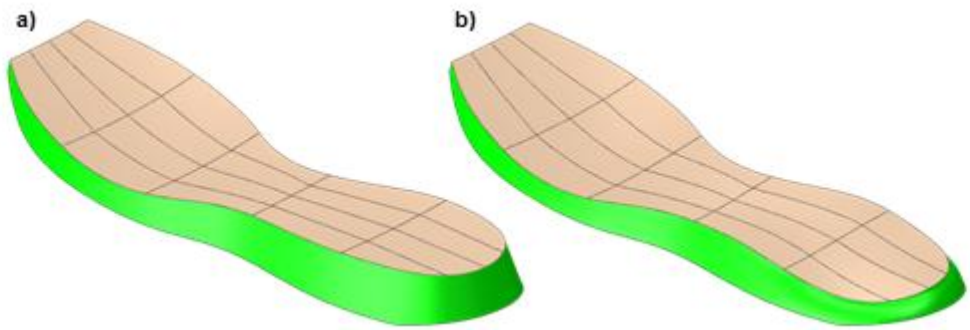

Figure 1. Base model used in midsole topology optimisation. a) Undeformed, and b) deformed.

2.2.2 Optimisation task

The objective function of the optimization task was to minimise strain energy whilst satisfying a constraint defined to ensure the midsole volume remained lower than 30 % of its original value. As such, the initial relative density of all elements in the design area was also set to be 0.3 with a standard density update strategy and maximum change per design iteration of 0.25 defined. The general (sensitivity-based) optimisation algorithm was found to be more robust for the modelled problem whilst a solid isotropic material interpolation (SIMP) technique specifying an exponential relationship between the density and stiffness of each element was selected due to the quasi-static nature of the defined problem.

The design area was identified to contain all elements contained within the midsole except those on the top surface. This was to ensure that the optimised geometry output remained as a single, continuous part. No strategy for the deletion of elements was included in the optimisation approach so all elements in the design area therefore retained a relative density of between 0.0 and 1.0. Global stop conditions were defined such that the optimisation would not exceed 50 design iterations although convergence was typically achieved after 35-45 designs had been simulated. Default values were selected for all other optimisation parameters. This approach resulted in a robust model capable of outputting midsole geometries optimised to be stiff but lightweight.

3. Results

Figure 2. Optimised midsole geometries output for each subject. a) Subject A (rearfoot striker), b) Subject B (rearfoot striker), and c) Subject C (forefoot striker).

Figure 2 shows the optimal distribution of midsole material for each of the three subjects as determined with ATOM. As is to be expected, material was retained in areas of high loading but removed in areas that experienced lower strains. This is highlighted by the clear differences in the optimised geometries output for the rearfoot (Subject A and Subject B) and forefoot (Subject C) strikers.

The midsole geometries output for Subject A and Subject B were similar but differences in the two subjects' footstrike loading profiles were manifested in the optimised geometries produced. For example, Subject B exhibited comparatively greater loading in the lateral rearfoot and under the metatarsal heads. This is reflected by a higher level of material retention in these areas.

The unconstrained structures presented in **Error! Reference source not found.** 2 are clearly of too great a complexity to be manufactured with traditional moulding techniques. To overcome this problem ATOM allows geometric constraints to be defined in order to encourage the development of manufacturable geometries. Figure 3 shows the optimised geometries output for Subject A and Subject B after an 8 mm minimum member constraint had been defined to prevent the generation of thin truss members.

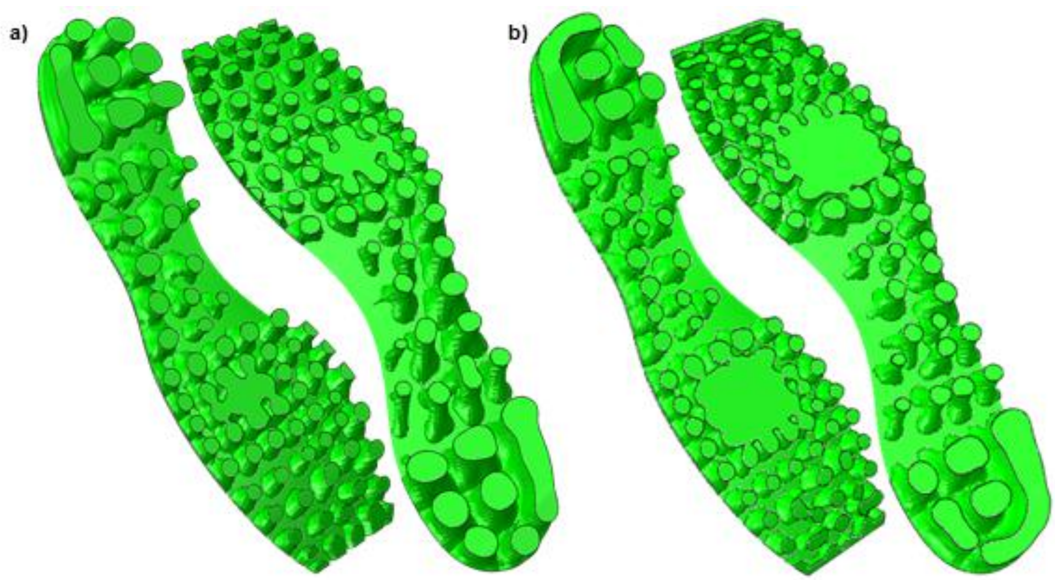

Figure 3. Optimised midsole geometries output for rearfoot strikers after defining an 8 mm minimum member size constraint. a) Subject A, and b) Subject B.

The differences in the geometries output for the two rearfoot strikers are more observable after the application of geometric constraints. The greater level of material retained under Subject B's metatarsal heads is clear whilst a more even distribution of material at the rearfoot of Subject A's midsole is also apparent.

4. Discussion

This paper has demonstrated that topology optimisation methods could potentially be employed to automatically generate lightweight midsole geometries optimised for a subject's individual footstrike loading pattern. Whilst this represents significant progress over a traditional, iterative design approach, there are a number of limitations to the reported methodology. These include a simplified material model, the applied boundary conditions and concerns about the manufacturability of the geometries output.

A crucial aspect of the methodology was that model load conditions were determined from biomechanical running trials. The load conditions were however calculated using an "assumption of proportionality" which was evaluated by Bruening et al. (2010) and found to result in peak absolute errors for the shear forces of up to 12 % bodyweight during normal gait. It was thus concluded that the method could lead to the some loss of information on foot function which would be manifested in the geometries output with the methodology reported here.

Furthermore, a fundamental drawback of applying topology optimisation in the design of footwear midsoles is that the stiffest structure is considered optimal (Nishiwaki et al., 1998), thus neglecting the primary role of the midsole, to dissipate footstrike impact forces. Based on the work of Sigmund (1997) and Frecker et al. (1999) into the design of compliant mechanisms with topology optimisation, a more advanced midsole optimisation methodology could be developed to overcome these issues with minimum displacement constraints defined for each of the 20 foot regions. Additional work is clearly required in this area to allow for the development of optimised custom midsoles that still maintain some degree of engineered compliance.

It has been shown that topology optimisation can be used to develop completely novel footwear designs but this process could not be considered as anything other than an interesting exercise to stimulate design ideas unless the geometries generated are actually manufacturable. Midsole geometries output after the application of geometric constraints were presented in Figure 3 but it is clear that further constraint and advances in manufacturing technology would be required before the mass customisation of functional footwear midsoles could become a feasible reality.

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