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Prediction of the effect of midsole stiffness and energy return using trajectory optimization

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Introduction

Several experimental studies showed the advantages of soft midsoles with high energy return on running economy (e.g. Worobets *et al.*, 2014, Sinclair *et al.*, 2014). Dorschky *et al.* (2019) showed these advantages in a virtual study, where running was simulated by solving trajectory optimization. The trajectory optimization predicted kinematics and kinetics including muscle activation and thus metabolic energy in response to different midsole materials.

However, it is unknown if running economy was improved mainly due to the increased softness or energy return. Such a study would be difficult to perform experimentally, due to the complexity of developing prototypes where only one property is varied. On the other hand, this can be modeled in a virtual study.

Purpose of the study

We predict the effect of midsole cushioning stiffness and energy return on running separately using trajectory optimization with randomized musculoskeletal models. To do so, we propose a method to quantify force-deformation behavior of shoe midsoles without prototyping.

Methods

Force-deformation curves were drawn manually, as mechanical test data was unavailable. Material A corresponded to ethyl vinyl acetate (EVA) and served as reference, B had more energy return and should have the same stiffness, C was softer and should have the same energy return, and D corresponded to thermoplastic polyurethane (BOOST™) which is softer and has a higher energy return (Fig. 1).

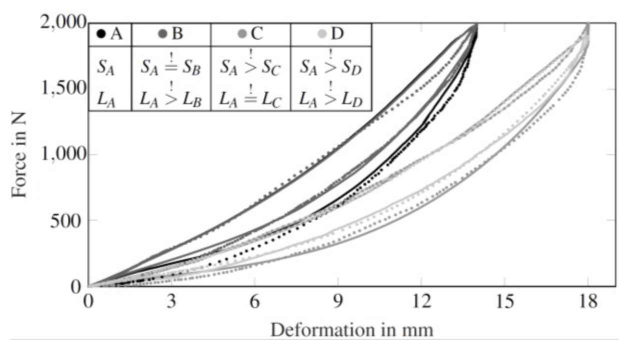

Figure 1. Force-deformation curves with stiffness S and energy loss L (dotted: sampled; solid: parameterized).

Force and deformation were sampled manually. The time dependency was obtained by fitting the sampled deformation with dynamic time warping to the deformation profile applied in mechanical tests. Finally, the behavior was parameterized as:

$$F(d, \dot{d}) = \alpha_1 d + \alpha_2 d^2 + \alpha_3 d^3 + \beta d \dot{d},$$

given the force F, deformation d, and deformation rate $\dot{d}$ (Dorschky *et al.*, 2019). The parameters α_1, α_2, α_3, and β were determined by least squares optimization constrained by the desired stiffness and relative energy loss.

A virtual simulation study was conducted with 280 randomized musculoskeletal models per material (Dorschky *et al.*, 2019). Stack height and shoe mass was equal for all materials.

Results

The constrained curve fitting resulted in R^2 values above 0.99. In a virtual cushioning test using the parameterized behavior, relative differences of stiffness and energy loss deviated less than 1.5 % when an exact match was desired (Fig. 1 and Tab. 1).

Table 1. Relative differences for stiffnesses and energy loss after parametrization and median relative difference of simulated metabolic cost. Stiffnesses were obtained between 10 to 20 %, 30 to 50 % and 50 to 75 % of the maximal force.

	A vs B	A vs C	A vs D
Stiffness 1	-0.7 %	-32.5 %	-32.2 %
Stiffness 2	-0.7 %	-16.4 %	-17.3 %
Stiffness 3	-1.1 %	-12.7 %	-14.2 %
Energy Loss	-32.2 %	-0.2 %	-32.6 %
Met. Cost	-0.21 %	-1.21 %	-1.51 %

The simulations resulted in a median relative reduction of metabolic cost of 0.21 % for increased energy return (A vs B), 1.21 % for increased softness (A vs C), and 1.51 % for both (Tab. 1). All metabolic cost reductions were significant according to two-sided Wilcoxon signed rank tests (α=0.001).

Discussion and conclusion

The effect of midsole stiffness and energy return were studied separately in a virtual simulation study using hand-drawn force-deformation curves. Our results confirmed that softer and more efficient shoes improve energy cost of running (Worobets *et al.,* 2014, Hoogkamer *et al.,* 2018). Furthermore, we showed that increasing softness improved running economy to a greater extent than relative energy return.

Our virtual simulation study highlights how trajectory optimization can provide insight into shoe design without prototyping. Furthermore, our simulations allow for a systematic analysis of how the musculoskeletal model achieves metabolic cost reduction.

References

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