Thermodynamics of Running Shoes: Energy Management, Heat Transfer, and Implications for Athletic Performance

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Running shoes can be modeled as compact thermodynamic systems, providing a practical example of applied energy and heat transfer principles. Each stride involves mechanical work, friction, and the conversion of energy into heat, all governed by fundamental physical laws. The performance and comfort of running shoes depend on how efficiently they manage energy and heat transfer, including storage, dissipation, and return. This analysis examines running shoes from a thermodynamic perspective, focusing on thermal processes during running, temperature-dependent material behavior, and design innovations that reduce energy loss while increasing comfort and performance.

I. INTRODUCTION

During running, metabolic energy is converted into mechanical work and heat. Due to low muscle efficiency, only 20 to 25 percent of this energy supports motion, while 75 to 80 percent is lost as heat (Rebay et al., 2007). Effective heat management by both the body and footwear is essential to prevent discomfort, overheating, or tissue damage. As shoe materials deform and recover with each stride, they store elastic energy and generate additional heat. Achieving an optimal balance between mechanical work and heat dissipation is a central thermodynamic challenge.

II. ENERGY BALANCE IN RUNNING SHOES

When viewed as a system, a running shoe's energy balance can be expressed as

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} = \frac{dU}{dt}, \tag{1}$$

where heat generated by friction ($\dot{Q}_{in}$) must be balanced by heat dissipation ($\dot{Q}_{out}$) and mechanical work input ($\dot{W}_{in}$). During running, this balance reflects a continual exchange of mechanical work and heat inside the shoe as it deforms and rebounds with each stride. Because midsole foams are viscoelastic, only part of the mechanical work done on the shoe is stored and later returned, while the rest is lost as heat through internal damping and hysteresis. Additional heat comes from friction and shear at the shoe–ground interface, especially during impact and toe-off, which adds to $\dot{Q}_{in}$. At the same time, $\dot{Q}_{out}$ depends on how well the shoe can conduct heat into the ground, allow airflow around and inside the upper, and support the evaporation of moisture from the foot and sock. These processes interact to determine whether the shoe's internal energy rises or falls during use. If heat builds up faster than it can escape, the temperature inside the shoe increases, which can soften temperature-sensitive foams and change how they respond to loading. As a result, the mechanical behavior of the shoe, including its cushioning, stiffness, and energy return, changes throughout the run.

III. MICROSCOPIC BEHAVIOR AND THE EINSTEIN MODEL

To interpret material behavior more analytically, the Einstein model of solids offers a useful framework for describing how running shoe materials respond to temperature at the microscopic scale. In this model, each atom functions as a quantum oscillator, storing energy in discrete units of hf, where h is Planck's constant and f is the vibration frequency. The material's temperature determines how many oscillators are excited and the total internal energy.

In foam midsoles, low temperatures reduce molecular vibration, increasing stiffness and decreasing the capacity to absorb or return energy. As temperature increases, more oscillators are excited, softening the foam and altering its pressure response. This principle accounts for the differing behaviors of common midsole materials such as ethylene vinyl acetate (EVA), thermoplastic polyurethane (TPU), and PEBA foam.

EVA is a lightweight, partially crystalline polymer widely used in running shoes. Its ordered molecular regions restrict thermal motion and raise the effective activation energy needed for oscillators to become excited. As a result, EVA becomes significantly stiffer in cold conditions; laboratory data from over 400 shoe models show that it can become up to 70 percent stiffer in low temperatures, reducing cushioning and flexibility. In contrast, TPU is an elastic, durable polymer composed of long molecular chains with primarily amorphous (disordered) arrangements. This lack of crystalline structure lowers the energy required for molecular vibration, allowing TPU to remain soft and responsive across a wide temperature range. PEBA, a high-performance foam, consists of alternating soft and hard molecular segments that form a flexible, low-density material with excellent energy return. Like TPU, PEBA is largely amorphous, which gives it stable mechanical behavior and high elasticity even in extreme temperatures.

These differences arise from each material's molecular structure and the way its molecules vibrate and store energy. EVA's more crystalline structure results in a higher Einstein temperature, rendering its oscillators inactive at lower temperatures and increasing overall stiffness. TPU and PEBA, with their disordered and thermally flexible molecular networks, have lower activation energies and therefore remain elastic as environmental temperatures change. This microscopic structure enhances cushioning, energy return, and overall performance during running.

IV. HEAT TRANSFER MECHANISMS

The movement of heat in running shoes depends on three main processes: conduction, convection, and evaporation. How well these processes function shapes both the thermal comfort and the overall performance of the shoe. Conduction, for example, is the transfer of heat through the solid materials of the shoe, following the principles described by Fourier's law

$$\frac{dQ}{dt} = -kA\frac{dT}{dx}, \tag{2}$$

In Equation (2), $\frac{dQ}{dt}$ represents the heat transfer rate, k is the thermal conductivity of the foam, A is the cross-sectional area through which heat flows, and $\frac{dT}{dx}$ is the temperature gradient across the material (with x denoting the direction of heat flow). Holistically, Equation (2) indicates that the rate of heat transfer by conduction is directly proportional to the thermal conductivity of the shoe material and the temperature gradient across it. The negative sign indicates that heat flows from regions of higher to lower temperature, consistent with the Second Law of Thermodynamics. In running shoes, heat generated by the foot dissipates through the midsole at a rate determined by the foam's conductivity and thickness. A steeper temperature gradient or a more conductive material increases heat flux, while thicker, more insulating foams reduce it, leading to greater heat accumulation during running.

Thermal conductivity, represented by k, is a key property of running shoe foams. Materials like EVA and PEBA are chosen in part because they have relatively low thermal conductivity—EVA typically measures about 0.18 W/m·K, while PEBA can reach around 0.35 W/m·K. This means that these foams act as insulators, helping to shield the foot from cold surfaces. However, this same insulating quality can become a drawback during long runs. When heat generated by the foot cannot escape efficiently—especially if the shoe's upper(the material covering the top of the foot) also restricts airflow—the result is a buildup of internal temperature. According to the Second Law of Thermodynamics, heat naturally moves from warmer to cooler areas, but when the midsole limits both conduction and air movement, this transfer is slowed, and heat accumulates inside the shoe.

Evaporation is a very efficient mechanism for removing heat. As human sweat vaporizes at the foot's surface, it removes about 580 kilocalories per liter of thermal energy. However, its effectiveness depends on airflow and humidity within the shoe. When fabrics such as socks and linings become saturated, evaporative heat loss drops sharply, causing heat to build up where sweat cannot escape. This accumulation affects the temperature-dependent behavior described by the Einstein model: as internal temperatures rise, molecular vibrations increase, softening most foams and changing their ability to absorb or return mechanical energy.

Recent research by RunRepeat (2025) shows that the thermal behavior of midsole materials is a significant factor in shaping the performance of running shoes in varying conditions. While precise measured specific heat capacity values for EVA, TPU and PEBA foams in footwear applications were not located in the literature, comparative evidence of their thermal behaviour (stiffness change, temperature sensitivity, heat retention) supports the view that their effective thermal responsiveness differs significantly. EVA, the most common material, becomes noticeably stiffer in cold temperatures and retains heat during use, which can influence both comfort and function. Compared to other materials, PEBA and TPU foams maintain their cushioning and energy return even as temperatures shift, and their higher thermal conductivity allows them to release heat more efficiently. These findings highlight how the selection of materials, the design of the midsole, and the relationship between the runner and the temperature of their environment each play a role in how running shoes regulate heat. Collectively, these findings indicate that heat transfer in running shoes depends on several interrelated factors. Midsole foam properties, airflow patterns, sweat evaporation, and material thermal responsiveness all influence heat movement through the shoe. All of these factors affect how the user experiences wearing the shoe.

V. EXPERIMENTAL OBSERVATIONS

Rebay *et al.* (2007) used thermocouples at the heel, arch, and forefoot to measure temperature changes during running. At 4 km/h, the heel showed the greatest temperature increase, about 2 °C. At 16 km/h, the highest temperature shifted to the toes, reaching approximately 6 °C, which corresponds to the forward movement of plantar pressure at higher speeds. After exercise, the heel cooled faster than other areas because heat was conducted through the sole into the ground. These results clearly indicate that both material properties and running mechanics jointly influence heat generation and transfer, emphasizing the multi-factor nature of thermal behavior in footwear.

Infrared thermography offers valuable insight into heat movement within running shoes.

Popovici and Budescu (2011) used thermographic imaging to monitor temperature distribution in different shoe models during and after exercise. They found that heat accumulates mainly at the front of the shoe, especially around the toes, where blood flow and friction are highest. Shoes with effective ventilation help release heat. The top-performing shoe maintained a stable internal temperature and cooled evenly after exercise. In contrast, the least effective model retained heat even after 10 minutes of rest. Popovici and Budescu recommend thermographic testing to help athletes choose shoes that match their individual heat and sweat patterns. The most comfortable shoes allow rapid heat escape and maintain internal thermal balance.

VI. ENERGY EFFICIENCY AND PERFORMANCE

In addition to comfort, material engineering enhances performance by increasing energy efficiency. Hoogkamer *et al.* (2017) evaluated prototype marathon shoes featuring lightweight, compliant foams and rigid carbon-fiber plates. In treadmill tests, elite athletes running at 14 to 18 km/h used approximately 4 percent less energy in these prototypes than in standard racing shoes. This improvement results from efficient mechanical energy storage and return, with minimal internal energy lost as heat. The carbon plate functions as a spring to reduce deformation losses, while the foam limits hysteresis. From a thermodynamic perspective, these shoes reduce entropy generation per stride, resulting in lower metabolic energy expenditure and improved running economy.

More recent research adds to this picture of how plate design influences performance. Song *et al.* (2024) reported that curved carbon plates can reduce forefoot loading and alter how forces travel through the foot during the stance phase. As shown in Figure 1, the geometry of the plate changes how forces are distributed through the foot and the midsole. Curved plates tend to spread the load more evenly and guide the force progression more smoothly toward toe-off, which can lower the amount of internal work at the ankle and reduce the muscular effort required for propulsion.

Overall, these findings highlight the combined effects of material properties and structural design on running efficiency. When deformation losses in the plate are reduced, hysteresis in the foam is minimized, and the path of ground reaction forces is shaped more effectively, the shoe helps conserve mechanical energy and supports better performance across different conditions.

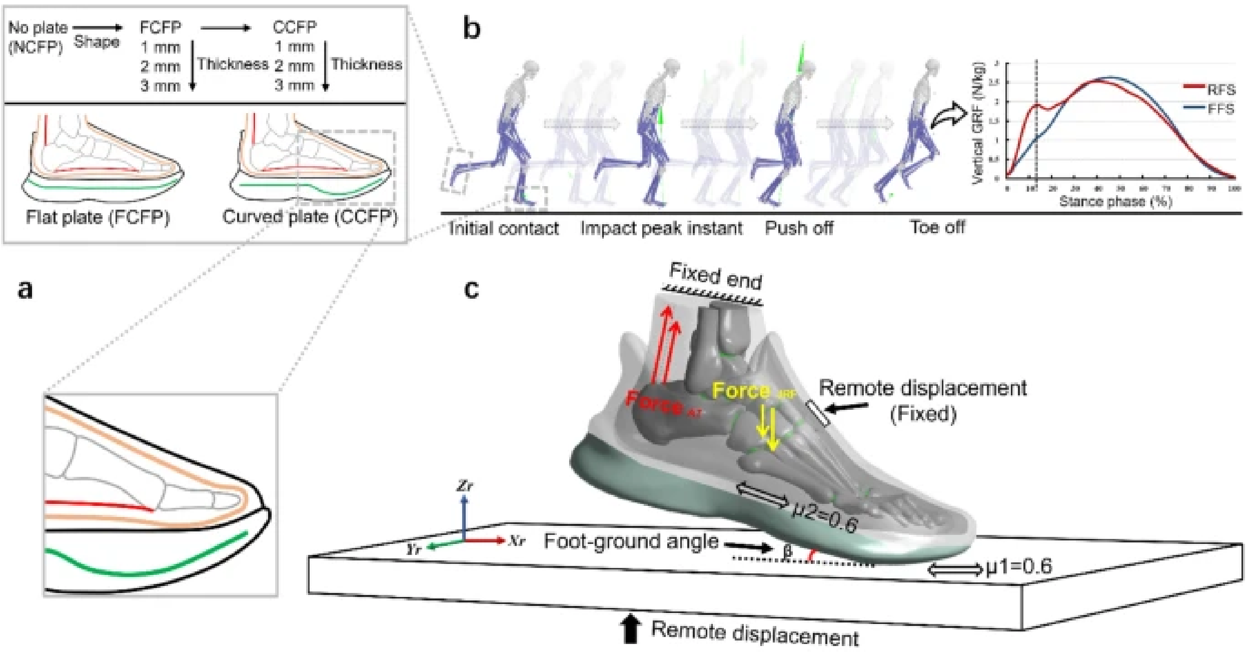

FIG. 1: Mechanical model from Song *et al.* (2024) illustrating how flat and curved carbon plates influence force distribution and stance-phase mechanics during running.

VII. DISCUSSION AND CONCLUSIONS

The thermodynamics of running shoes involve both thermal comfort and mechanical efficiency. The laws of heat flow and energy balance govern the interaction between a runner's foot and the shoe. Frictional heat must be balanced by dissipation and mechanical work input. Optimal running shoes reduce heat buildup, enhance heat dissipation, and store mechanical energy elastically instead of losing it as heat. Materials like PEBA foams and carbon-fiber plates help achieve these outcomes by maintaining stable properties across temperatures, efficiently returning energy, and supporting thermal balance during extended use.

In summary, the thermodynamics of running shoes demonstrate a direct link between microscopic material behavior and athletic performance. The Einstein model explains how molecular motion affects foam stiffness and energy storage. Fourier's law describes heat transfer within shoes, while the Second Law of Thermodynamics underscores the importance of heat dissipation and sweat evaporation for runner comfort. Research by Rebay *et al.* (2007) and Popovici and Budescu (2011) shows that shoe temperature is affected by both running style and design, and Hoogkamer *et al.* (2017) provide evidence that advanced materials enhance real-world performance. These findings suggest that future shoe designs should minimize energy loss and heat buildup while improving comfort and speed through effective heat and energy management.

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