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Injuries and Footwear (Part 2)

Minimalist Running Shoes

Joseph J. Knapik, ScD; Robin Orr, PhD; Rodney Pope, PhD; Tyson Grier, MS

ABSTRACT

This article defines minimalist running shoes and examines physiological, biomechanical, and injury rate differences when running in conventional versus minimalist running shoes. A minimalist shoe is one that provides "minimal interference with the natural movement of the foot, because of its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices." Most studies indicate that running in minimalist shoes results in a lower physiological energy cost than running in conventional shoes, likely because of the lower weight of the minimalist shoe. Most individuals running in conventional shoes impact the ground heel first (rearfoot strike pattern), whereas most people running in minimalist shoes tend to strike with the front of the foot (forefoot strike pattern). The rate at which force is developed on ground impact (i.e., the loading rate) is generally higher when running in conventional versus minimalist shoes. Findings from studies that have looked at associations between injuries and foot strike patterns or injuries and loading rates are conflicting, so it is not clear if these factors influence injury rates; more research is needed. Better-designed prospective studies indicate that bone stress injuries and the overall injury incidence are higher in minimalist shoes during the early weeks (10–12 weeks) of transition to this type of footwear. Longer-term studies are needed to define injury rates once runners are fully transitioned to minimalist shoes. At least one longer-term minimalist-shoe investigation is ongoing and, hopefully, will be published soon.

KEYWORDS: *injuries, foot; footwear; shoes, minimalist; shoes, conventional; shoes, running*

Introduction

Within the past 12 years, minimalist running shoes have gained popularity as an alternative to modern, high-technology running footwear. Advocates argue that running in minimalist shoes is closer to barefoot running, for which humans are naturally adapted through years of evolution, while opponents argue that the foot is better protected by the stability, support, and superior cushioning provided by modern running shoes.[1] In this article, we first define the minimalist shoe, then review physiological and biomechanical differences between running in minimalist and conventional footwear and examine studies that have compared injury rates based on biomechanical differences and running in the two types of footwear.

It is important to note that we are only considering studies that have looked at conventional and minimalist footwear. Minimalist footwear was developed by running shoe companies in response to the "barefoot movement," the movement away from shoes altogether in favor of running barefoot.[2] In the US military, barefoot running is not permitted in regular unit training and some form of running footwear is required. Thus, this review only includes studies that compare minimalist and conventional footwear. This is the second part of our review of footwear and injuries. Part 1 covered the history of athletic footwear, how selecting footwear based on arch height affects injury rates, and provided an historical comparison of injury incidence when running in shoes versus boots.

What Is a "Minimalist Running Shoe"?

A definition of a "minimalist shoe" was developed by a group of 43 people who were primarily running shoe

researchers and healthcare practitioners.[3] They participated in a long process that involved identifying and discussing the characteristics of shoes of this type. The definition they developed for a minimalist shoe was "footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices." A "minimalist index" was developed to determine the degree of minimalism in the shoe. The minimalist index included the following: shoe weight, stack height (height of the shoe in the middle of the heel), heel to toe drop, amount of stability/motion control technologies, and flexibility. Each of these characteristics was rated on a scale (0–5 points), with the final index expressed as a percentage of the total possible points. A separate study involving 85 individuals who applied the minimalist index to a variety of running shoes found excellent agreement between raters (interrater reliability 0.84–0.94).[3]

Some have subdivided minimalist shoes into at least two broad categories: barefoot and cushioned.[4] These are generally characterized by the amount of cushioning material between the foot and the ground and by the degree of drop (angle) from the heel to the toe. Barefoot-type shoes are little more than thin foot coverings offering protection from running-surface hazards. The soles are very flexible and have no arch support, very little material between the foot and the ground, and no drop from the heel to the toe. Cushioned shoes have more material between the foot and the ground, to provide some cushioning. There is usually some degree of drop from the heel to the toe but little or no arch support. Examples of the two types of minimalist shoes are shown in Figure 1.

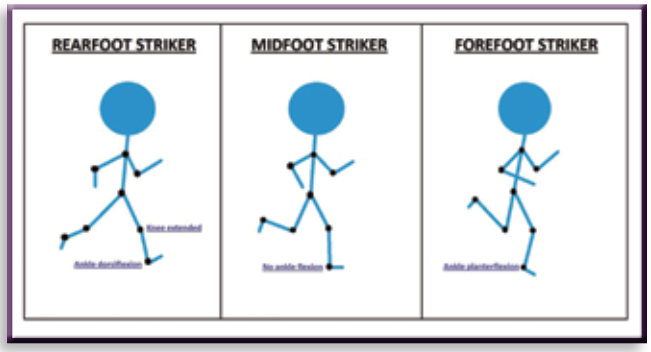
Physiological/Biomechanical Differences: Minimalist Versus Conventional Running Shoes

Studies that have compared minimalist with conventional running shoes have found differences in physiological responses and running biomechanics. Running in minimalist shoes generally resulted in a lower physiological energy cost than did running in conventional shoes, in most studies.[5–8] This is likely because many minimalist shoes are lighter than conventional shoes. During running, the foot and the leg are accelerated and decelerated during each gait cycle, and lighter shoes require less muscular force to produce these changes in movement. Less muscular force results in a lower energy cost. It is estimated that the energy cost of running increases by about 0.7–1% for every 100g of additional shoe weight.[9,10] Thus, the lighter the shoe, the lower is the energy cost of running.

Other differences between these two types of shoes have to do with the mechanics of running. There are three major ways runners contact the ground; these are illustrated in Figure 2. In the rearfoot strike, the foot is more dorsiflexed (pointed upward at the ankle), increasing the loading requirement of the anterior tibial muscles (front of the shin); contact is on the lateral (outside) part of the heel; and the knee is extended. The muscles of the thigh (vastus muscles) must absorb much of the force of impact using eccentric (lengthening) muscle contractions. In a forefoot strike, the foot impacts the ground on the front of the foot with a slight plantarflexion (foot extended at the ankle) and more knee flexion, thus making the lower limb less rigid and more able to adapt the foot to the landing surface. A midfoot strike pattern is intermediate between the rearfoot and forefoot, with the heel and forefoot striking the ground almost simultaneously. Studies have suggested that 72–95% of people who wear conventional shoes contact the ground with a rearfoot strike pattern.[11–14] Among runners who have never before run in minimalist shoes, the proportion of rearfoot strikes is highest in a conventional shoe, lower in cushioned minimalist shoe, and lowest in a barefoot minimalist shoe.[4,15] The majority of runners who have been using minimalist shoes for some time strike the ground with a forefoot or midfoot strike pattern.[6,14] One study showed that 6 weeks after transitioning to minimalist shoes, only 36% of runners were still using a

Figure 1 *Examples of barefoot and cushioned minimalist running shoes.*

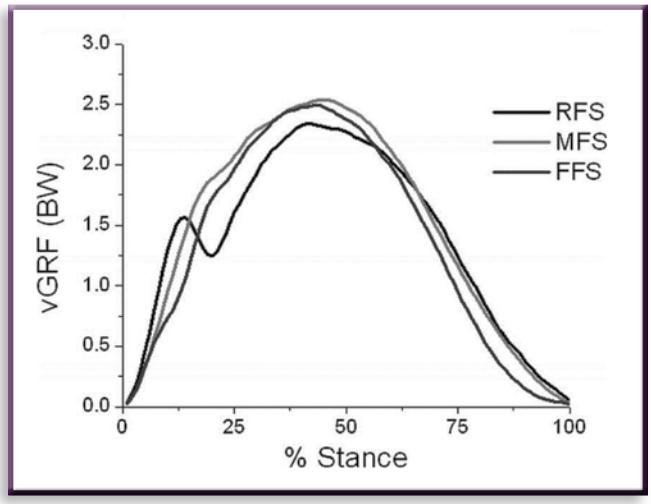
Figure 2 *Joint functions for rearfoot, midfoot, and forefoot strike patterns during running.*



rearfoot strike pattern, whereas 57% were using a forefoot strike pattern.[14] These investigations indicate that over a relatively short time, most runners adapting to minimalist shoes adopt a forefoot strike pattern.

Figure 3 shows vertical ground reaction forces for forefoot, midfoot, and rearfoot ground strikes.[1,16,17] Vertical ground reaction forces are the vertical forces of impact on the ground—in this case (Figure 3), measured in terms of body weight. All foot strike patterns have a similar peak impact force (about 2.5 times body weight). However, the rearfoot strikers have a greater rate of force development (called the loading rate) and an initial peak (at about 1.5 times body weight) that precedes the peak impact force. Note that midfoot strikers have a loading rate that lies between rearfoot and forefoot strikers.[1]

Figure 3 *Vertical ground-reaction forces (VGRF) for rearfoot strikers (RFS), midfoot strikers (MFS), and forefoot strikers (FFS) wearing running shoes. The line showing two peaks is for RFS. Note that loading rates (slopes of initial VGRF) are highest in RFS, lower in MFS, and lowest in FFS. BW, body weight.*



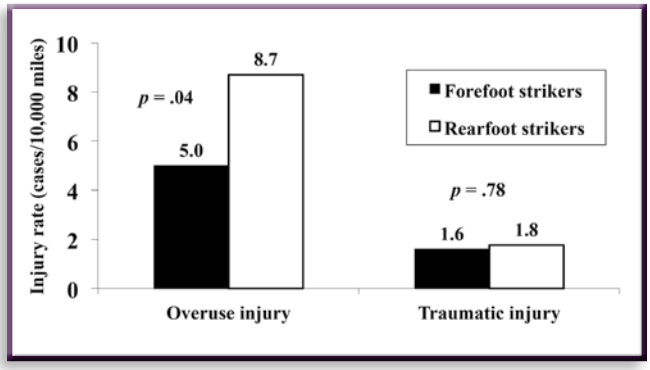
Data from Altman and Davis.[1]

In summary, the major biomechanical differences between running in conventional versus minimalist shoes appear to be a lower energy cost of minimalist shoes, associated with the lighter shoe weight; and the gradual adoption of a forefoot or midfoot strike pattern. The forefoot strike typical of runners wearing minimalist shoes generally results in a lower loading rate when the foot hits the ground.

Injuries and Foot Strike Patterns

There are some limited data on associations between foot strike patterns and injuries. One study[18] examined this association in 52 Division I National Collegiate Athletic Association runners at Harvard University. The runners competed in distances from 800m to 10km and ran an average of about 71km/week (44 miles/week). The runners were filmed as they ran on either a treadmill or a track, and their foot strike patterns were assessed on viewing the film. There were 16 forefoot strikers (31%) and 36 rearfoot strikers (69%). Injuries were recorded by an athletic trainer/physical therapist with follow-up consultations with physicians. A complex injury severity score was developed based primarily on the number of days of activity restriction and the types of restrictions. Injury rates by foot strike patterns are shown in Figure 4. At the end of the study period (about 2 years), the moderate to severe overuse injury rate was higher for the rearfoot strikers, but there was no difference by foot strike pattern for traumatic injuries.

Figure 4 *Moderate to severe overuse and traumatic injury incidence by foot strike patterns among Harvard University runners.*



Data from Daoud et al.[18]

Another study[19] examined whether transitioning individuals from a rearfoot to forefoot strike pattern might affect chronic exertional compartment syndrome (CECS). In CECS, exercise results in the swelling of the lower leg that increases intramuscular pressures and results in a reduction in blood flow, with severe pain and disability. Ten military personnel at the US Military Academy (West Point, New York) who had CECS and were scheduled for surgery to alleviate this condition were enrolled in a 6-week training program that involved transitioning from a rearfoot to a forefoot strike pattern. Six weeks after the start of the program, the runners had considerably reduced lower-leg compartment pressures during running, reported less pain on running, and had considerably increased their running distance. One potential reason for this reduction in CECS could be the reduced requirement to dorsiflex the foot in preparation for heel strike. This, in turn, would unload structures that may have been chronically loaded over years of exposure to heel strike running. No patient required surgery after the program and, 1 year later, the patients reported their lower leg function remained considerably improved compared with before the training program.

A final study[20] examined foot strike patterns and self-reported injuries among 341 male Soldiers in the 1-66th Armor Regiment stationed at Fort Carson, Colorado.

Foot strike patterns were assessed by high-speed filming, and injury data were obtained from a questionnaire. Injuries were limited to those that required modified training for at least 1 week because of pain or discomfort and that occurred as a result of running. There were 296 rearfoot strikers (87%) and 45 nonrearfoot strikers (13%). The proportion of Soldiers reporting any lifetime running injuries was 50% in rearfoot strikers and 56% in nonrearfoot strikers ($p = .51$). Over the previous 5 years, overuse injury incidence was also similar for Soldiers with these foot strike patterns (rearfoot strikers, 32%; nonrearfoot strikers, 31%; $p = .89$). It is not clear how many miles the Soldiers were running, but estimates from the data provided in the article suggest an average of about 12 miles/week.

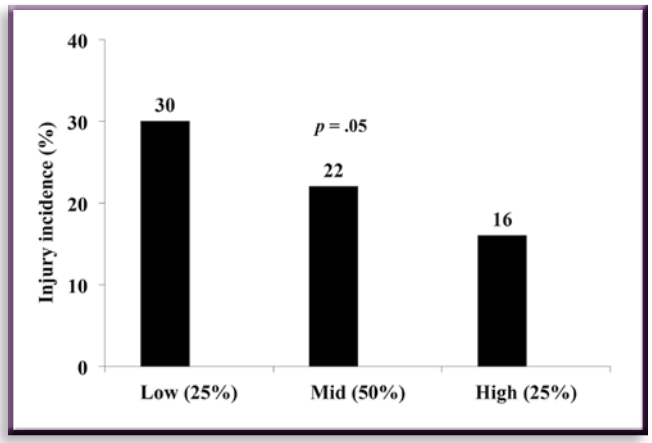
Thus, it is not clear at this point if the running foot strike pattern influences injury incidence, although there is likely benefit for individuals suffering from CECS in adopting a forefoot strike pattern. The Harvard study suggests that elite runners who perform longer weekly distances may benefit from a forefoot strike, but one problem with this study was that foot strike patterns were not assessed for the entire length of the investigation; some athletes may have adopted another foot strike pattern later in the study. The Fort Carson study suggested that among Soldiers who run limited weekly distances, there is no difference in injury incidence by foot strike pattern. One serious limitation of the Fort Carson study was the self-reporting of injuries over long time periods (lifetime and 5 years). Studies have shown that recall of injuries progressively decreases as the recall period increases.[21,22] In addition, it should be noted that Soldiers undertake a wide variety of activities, with running usually representing only a small proportion of their regular physical activity. Thus, it is likely that any influence of running foot-strike pattern on long-term injury rates may have been masked in the Fort Carson study by the strong contributions to injury rates by many other types of Soldiers' physical activities.

Injuries and Loading Rates

A number of studies[23–28] have compared loading rates between runners who had a prior stress fracture or plantar fasciitis and runners without these injuries. Most studies[23–25,27,28] matched injured and uninjured subjects on characteristics like age and running mileage. Some studies found that the runners with the injuries had a greater loading rate on ground contact than did runners without these injuries,[23–25] but other studies did not find a difference.[26–28] A few of the studies finding positive results[23,24] admitted the most serious limitation to studies of this type: it was not clear if the more-rapid loading rate was present before the injury, or if it had developed after the injury.

The only study to prospectively examine the association between loading rates and running injuries was that of Nigg,[29] in which data from a previous study were reanalyzed. These data included 131 runners who had their loading rates obtained before the start of the study. In the subsequent 6 months, injuries were tracked by a sports medicine physician. Runners were separated into three groups, representing low, moderate, and high loading rates, and injuries were examined in each of these groups. Results are shown in Figure 5 and were not what might be expected: injury rates declined as impact forces increased.

Figure 5 *Association between running injuries and prospectively obtained loading rates. Approximate p-value was calculated based on data from Nigg.*[29]



Despite being somewhat counterintuitive, the finding that injury rates declined with higher impacts is consistent with research on bone strength that suggests high impacts may reduce the possibility of at least one type of injury: those involving bone stress. Individuals participating in sports involving high impacts (e.g., basketball, volleyball, running) have higher bone mineral density than those in nonimpact sports (e.g., swimming).[30–32] In a different type of study, Warden and colleagues[33] repeatedly mechanically loaded rat bones for short bouts, 3 days per week for 5 weeks, and found that this regular repetitive loading resulted in a twofold improvement in the structural properties of the bone over that time period. Most importantly, however, this twofold improvement in the bone structure provided a 100-fold increase in the resistance of the bone tissue to fatigue and damage when it was repeatedly loaded to the same level in a single session until it broke. Thus, high impacts may improve bone strength and lower the risk for bone stress injuries, but how high impacts may influence other types of injuries involved in running is not clear.

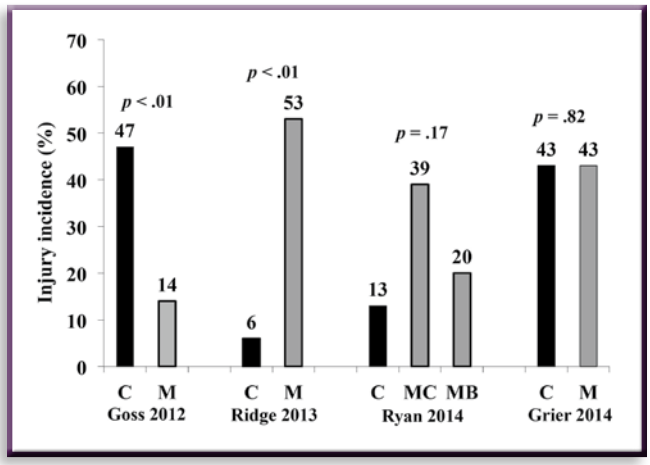
Like the data on foot strike patterns, data on associations between impact forces and running injuries do not present a well-defined picture. It is not clear if loading

rates are related to running injuries. This lack of clarity results from the limitations of the cited retrospective studies, the mixed results from these retrospective investigations, and the fact that the only prospective study found that runners with higher loading rates were less likely to be injured.[29] However, it is notable that higher impact forces are associated with greater bone mineral content and density,[30–32] and this finding is consistent with investigations suggesting that regular short bouts of relatively high levels of repeated loading of bone strengthen the bone tissue in such a way that it is resistant to damage from future repeated loadings.[33] Future studies that prospectively examine loading rates and subsequently track injuries in larger groups of runners are necessary to determine associations between loading rates and running injuries.

Injuries in Minimalist Versus Conventional Running Shoes

To date, there are at least four studies that have compared injury rates in minimalist versus conventional running shoes. The earliest of these (Goss et al.[34]) recruited 2,509 runners from universities, running websites, and personnel at Fort Sam Houston, Texas. Participants who were 18–50 years old and ran at least 6 miles per week were simply asked to complete a questionnaire. Runners were included in the analysis only if they reported that they had not changed their foot strike pattern or shoe type in the past year, if they were sure of their foot strike pattern and shoe type, and if they completed a question involving injuries. There were 904 runners who met all these criteria and, thus, were included in the study. Runners who reported wearing conventional running shoes were 3.4 times more likely to report injuries compared with those wearing minimalist shoes, as shown on the left in Figure 6.

Figure 6 *Results of four studies[34–37] that compared injury incidence in conventional versus minimalist running shoes. C, conventional shoes; M, minimalist shoes; MB, minimalist barefoot shoes; MC, minimalist cushioned shoes.*



A study from Brigham Young University, by Ridge et al.,[35] compared bone stress injuries in runners using conventional versus minimalist shoes. Runners who participated in this study had never used minimalist shoes, were injury free, and ran an average of 15–30 miles/week in the 6 months before the study. Investigators randomized subjects into two groups: one that continued running in conventional shoes for 10 weeks (n = 17) and one that gradually transitioned into a Vibram 5-Fingers shoe (Vibram SpA; http://www.vibram.com) over the 10-week period (n = 19). The transition program in the minimalist shoe group involved progressively increasing the participant's running distance in the Vibram shoe while decreasing mileage in their usual conventional shoe. Bone stress injuries (i.e., bone marrow edema determined by magnetic resonance imaging [MRI]) were assessed at the start of the study and after 10 weeks. The results are shown in the center left of Figure 6. MRI changes indicative of bone stress injuries were almost nine times higher in the minimalist footwear group after 10 weeks.

Another study, conducted in Vancouver, Canada, by Ryan et al.,[36] recruited runners through newspapers and word of mouth. Runners who participated in the study were 19–50 years old, had at least 5 years of running experience, had been regularly running 20–40km/week (12–25 miles/week) for the past 6 months, and had no injuries at the time of the study. Runners were randomized to three groups: one assigned a conventional shoe (Nike Pegasus 28; Nike Inc, www.nike.com), another assigned a cushioned minimalist shoe (Nike Free 3.0), and a third assigned a barefoot minimalist shoe (Vibram 5-Fingers). Runners then participated in a supervised 12-week training program in which they gradually increased running volume in preparation for a 10km race. They also gradually increased the amount of time wearing their assigned shoes from 19% of training time in week 1 to 58% in week 12. Injuries experienced in the three groups during the 12 weeks are shown on the center right in Figure 6. If we combine the results from the two minimalist shoes, runners in conventional shoes tended to have fewer injuries than did runners in the two combined minimalist groups (13% versus 28%; p = .08). The authors concluded that those new to minimalist footwear had higher injury risk and that caution should be exercised among those new to this type of footwear.

The final study, by Grier et al.,[3], examined injuries in the 4th Brigade of the 4th Infantry Division at Fort Carson, Colorado. The study involved 1,332 male Soldiers who either wore conventional running shoes or minimalist shoes. Shoe models and brands were recorded by the investigating team, and a Soldier was included in the study only if he indicated that the shoe examined was

his regular training shoe. The type of shoe (conventional or minimalist) was determined by the manufacturer's descriptions. Injuries to the Soldiers were examined in a 12-month period before the shoe examination. This study found there was virtually no difference in injury rates between those wearing conventional versus minimalist shoes (Figure 6, far right).

Although these four studies of minimalist footwear and injuries appear to present somewhat confusing results, let us take a critical look at each. Acknowledged limitations of the earliest questionnaire study[34] were mostly related to the self-reporting of information and the nature of the runners recruited. The authors noted that one of their previous studies indicated that 69% of runners were able to distinguish between rearfoot and forefoot strike patterns. Thus, there may have been some mistakes in reporting foot strike patterns. The question used to obtain injury data was well stated, but injuries were self-reported rather than obtained from medical records and participants may not have remembered all injuries they experienced. Minimalist-shoe runners reported more years of running and may have been a self-selected group. They may have better known how to avoid injuries, whereas those with continued injury problems may have ceased running and not been included in the study. Finally, it was possible that the minimalist shoe runners who were recruited were those most enthusiastic to share their experiences, resulting in a biased sample.

In the Fort Carson study,[37] it was not clear how long the Soldiers were using their shoes or if the injuries were directly related to running, since the study only examined total injury incidence in the past year. On the other hand, the Vancouver[36] and Brigham Young University[35] studies had well-defined groups of participants and prospectively tracked running-related injuries. Despite these favorable study characteristics, the two studies[35,36] followed the runners for only 10–12 weeks and minimalist-shoe runners were not fully adapted to the new footwear, since participants were not performing all their training in the new shoes by the end of the investigations. Nonetheless, these two prospective studies do suggest that injury rates are higher during the transition period from conventional to minimalist shoes. In addition, there are several case series of runners who were injured during transitioning to minimalist shoes[38] or switching to minimalist shoes without any transition.[39]

Longer-term investigations are needed in which runners are followed not only during the transition period but also for periods when they are fully adapted to minimalist shoes. One ongoing project[40] is conducting a 26-week, prospective, randomized controlled trial comparing individuals training in conventional versus minimalist shoes. Investigators will collect data on foot strike patterns, energy cost, and other measures. These data will be obtained at the start of the study, at 6 weeks, and at 26 weeks. Injuries will be tracked during the entire 26-week period. Findings from this study should add considerably to our knowledge on running mechanics and injuries related to minimalist footwear.

Until better and more consistent evidence is available, runners should pick shoes based on the recommendations from the American College of Sports Medicine (ACSM). The ACSM has a two-page guide on the selection of running shoes. The guide is available at https://www.acsm.org/docs/brochures/running-shoes.pdf. Also, the US Army has a minimalist running shoe website (http://armymedicine.mil/Pages/Minimalist-Running-Shoes.aspx) that contains practical information on US Army–approved types of running shoes and a transition program for switching from conventional running shoes to minimalist shoes.

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Disclosure

The authors have nothing to disclose.

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