Effects of Heel Height and Shoe Shape on the Compressive Load Between Foot and Base

A Graphic Analysis of Principle

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Even in the ever-changing and increasingly technical realm of medicine, commonsense approaches are needed. We can still learn from our predecessors by using their practical and simple methods. In this article a graphic approach in the sagittal plane is used to explain the relationship between the heel height of a shoe and load under the foot. By using an elementary theoretical model based on schematic sketches, an analysis of principle can be performed to calculate the change in the distribution of mechanical stress in the planta with change in foot orientation. The model shows that when standing posture remains unaltered, load under the forefoot increases and load under the heel decreases with elevated heel height and the corresponding changes in shoe shape. These results can be confirmed by pedobarographic and gait-analysis measurements, but the graphic method can be used without application of advanced instrumentation. The rationale behind the model is to use common terms and simple means to facilitate a more fundamental understanding of complex mechanical orthopedic problems. The method is meant to be a helpful supplement to clinical judgment in the many situations in which advanced instrumentation is not available. (J Am Podiatr Med Assoc 94(5): 461-469, 2004)

The effects of good- *versus* poor-quality footwear have been discussed for centuries, and associations between sore feet and fashionable shoes have been of particular interest. High-heeled shoes have existed since 2000 BC, and for more than 250 years physicians have discussed the effects of heel height on the wearer's health.[1, 2] Today, high-heeled shoes are used as a therapeutic measure in the treatment of tendinitis and partial ruptures of the Achilles tendon.[3] Several objective pedobarographic measurements have shown increased load under the forefoot as a result of heel lift,[4-8] but a comprehensive explanation of why these results occur is usually not presented. Thus a valid mental image for a more profound understanding of the problem is warranted. A subtle but not too advanced analysis to explain the complex and many detailed mechanisms behind the measured results is preferable.

A schematic and graphic model originally used by one of us (T.W.) for educating students and based on well-established theories provides a visual representation of the interdependence of the elevation of shoe heels and the distribution of forces under the

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foot. The model may help podiatric physicians understand how changes in the position of the ankle joint affect the forces between the patient and the shoe. It could also be applied to determine the effects on the foot of orthopedic appliances. A simplified graphic analysis model could be useful for elucidating and explaining the forces to which the foot is exposed during high-heeled gait. The model can predict how alterations in external forces influence internal forces in a defined system (free-body diagram)[9] such as the foot. This qualitative approach to an orthopedic problem will facilitate understanding of the biomechanics of a particular situation and determination of the most appropriate footwear for a given subject.

In this study, we analyze the isolated influence that different heel heights and shoe shapes might have on compressive loads beneath the sole of the foot and around the ankle joint. The instantaneous analysis is independent of body posture, and the depictions of various situations presented here should be representative of and reproducible for moments occurring during normal oscillations when standing at ease.

Methods

The compressive load between foot and base varies with the phases of the gait cycle, the individual's gait pattern, and the shape of the shoe, including heel height, heel seat, longitudinal arch (gelenk) under the midfoot, and shoe upper. A simplified version of the foot is the basis of the applied graphic analyses. The foot is seen as a two-dimensional (2-D) model composed of idealized solid segments extracted in the sagittal plane (first ray) with the foot oriented medially. The person stands at ease. The angle of the ankle joint varies with different shoe heel heights. To compare the various situations presented graphically here, the force of gravity and the size of the foot are assumed to be constant. The line of action of the force of gravity was chosen to be tangential to the front edge of the tibia at the ankle joint. Thus the line of action relative to the ankle joint is independent of the joint position, ie, the heel height. Consequently, the moment of force, which the force of gravity creates in the ankle joint, will be constant. Then the effects of raising the heel, curving the last, and shaping the shoe upper *per se* can be evaluated.

The body weight is kept in equilibrium by the resultant of the reaction forces under the foot. This means that the ground reaction force also has unchanged orientation and position relative to the ankle axis. If the location of the line of gravity had been chosen relative to a point of orientation on the foot, such as the os naviculare, the course of the force of gravity would have depended on the angle of the ankle joint (Fig. 1). This would affect the moment that the body weight creates in that joint.

The transitional forces between the substratum (shoe/ground) and the foot are seen as concentrated forces. It is also assumed that no interface shear forces are acting between the foot and the footwear. The forces acting between the shoe and the foot act at a right angle to the surface of the foot and are considered to be compressive forces (Fig. 2). The forces under the forefoot and heel are F and H, respectively, and the force of gravity is A (action). In the 2-D sagittal model, the forefoot is represented by the medial ray of the foot alone. The lateral foot brim is not considered. The system being analyzed is the patient and the foot as a whole.

All analyses are limited to static equilibrium situations in the sagittal plane. The upright posture describes approximately the same situation as early midstance in the gait cycle.

There is general agreement from objective measurements that the load under the foot in a normal upright position primarily is unevenly distributed between the ball of the foot and the heel. The distribution of the force is somewhat vague, but most authors[10-13] agree on a forefoot-to-heel ratio of approximately 2:3 when the total load distribution under the foot is described. In our model, this distribution may be different, as we have chosen a moment analysis when standing at ease with a specific and constant course of the gravity's line of action.

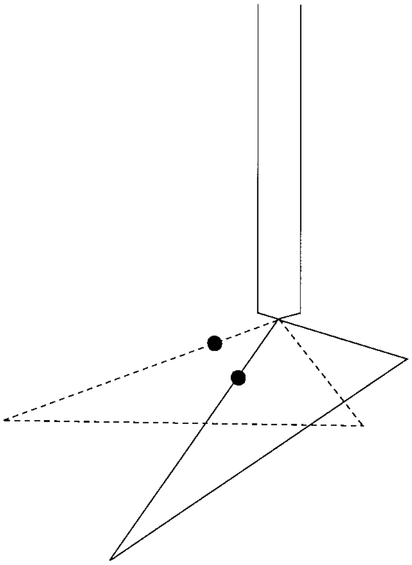

Figure 1. The point of orientation on the foot (black dots) in relation to the ankle joint depends on the angular orientation of the foot.

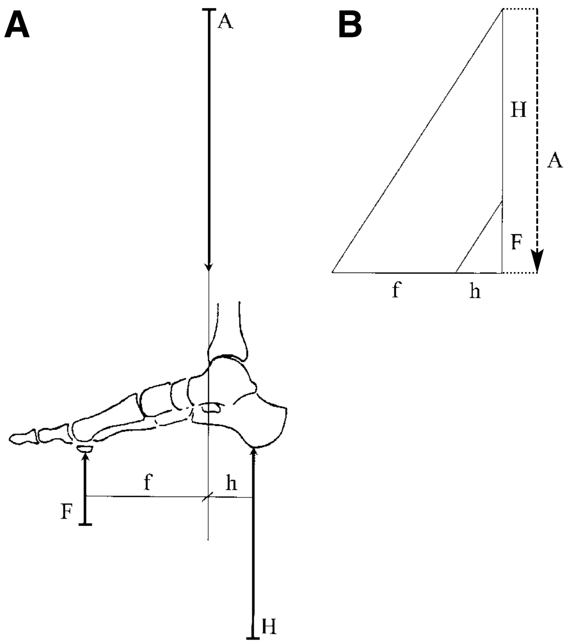

Figure 2. A, The forces under the forefoot (F) and heel (H) and the force of gravity (A) acting on the foot when standing without shoes. System: Whole body. B, Supporting illustration to determine F and H. Note that f and h represent moment arms.

The graphic analyses of principle are solved through constructional drawings based on considerations of static equilibrium between two or more forces, ie, the resultant forces acting on the body and the sum of rotational moments must be zero. The constructions assume that the position, direction, and magnitude of the force of gravity are known. As for the other forces, only lines of action and directions are known.

In the "Results" section, auxiliary constructions are used to explain how to determine the magnitude of three parallel forces graphically when they are in static equilibrium. The force of gravity (A) has a known line of action, direction, and magnitude. The point of application, line of action, and direction of the forces under the forefoot (F) and heel (H) are assumed. The equation A = F + H is valid.

By constructing two congruent triangles, it is possible to determine the magnitude of forces F and H (Fig. 2B). One side of the full-size triangle has the length A. The sum of moment arms f and h makes another side of the triangle. Force A is divided in proportion f/h by a line parallel to the third side, drawn from the division point between h and f. The construction results in the relation F/H = h/f, which leads to the equation of rotational moments: F × f = H × h. The forces F and H are inversely proportional to their moment arms.

In the present work, we study five different situations: no heel height, moderate heel height, extreme heel height, extreme heel height with oblique heel seat and forces from the shoe upper, and moderate heel height with support under the midfoot. In the ankle joint, the foot has three positions. In the last two illustrations, the shape of the shoe also has been considered. The analyses show how the compressive forces between the foot and the shoe change with alterations in the position of the ankle joint and the shape of the shoe.

Results

Figure 2 demonstrates the forces acting on the planta when the patient is standing and is not wearing shoes. The force under the forefoot (F) has the moment (lever) arm f to the line of action of force A, and the force under the heel (H) has the moment arm h. The forces under the forefoot and heel create equally large and opposite-directed moments around A's line of action.

In Figure 3, the subject is wearing shoes of moderate heel height and is otherwise standing as shown in

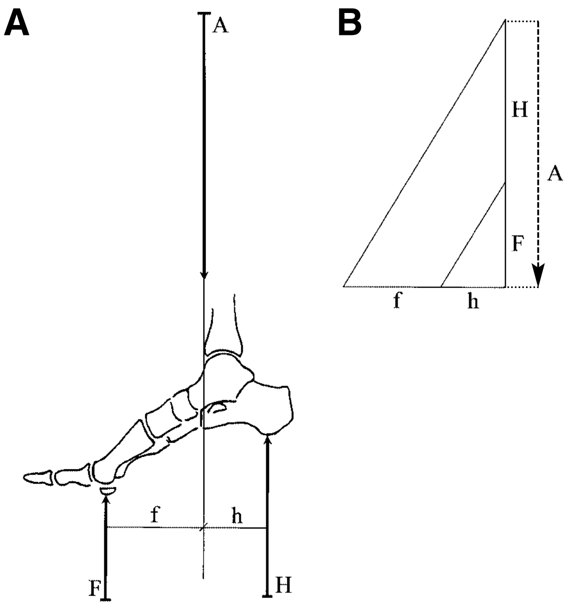

Figure 3. A, The forces under the forefoot (F) and heel (H) and the force of gravity (A) acting on the foot when standing and wearing shoes with moderate heel height and a horizontal heel seat. System: Whole body. B, Supporting illustration to determine F and H. Note that f and h represent moment arms.

Figure 2. The alteration of the foot's position with respect to the ankle joint caused by the elevation of the heel leads to a reduction in lever arm f and an increase in lever arm h. As the forces F and H must form equally large and opposite rotational moments around A's line of action, the two forces must change in magnitude compared with the situation shown in Figure 2. The conditions of equilibrium of forces and moments are the same as in Figure 2. The graphic illustration shows that in the heel lift situation, the force under the forefoot (F) is increased and the force under the heel (H) is reduced.

In Figure 4, illustrating an extreme heel lift, moment arms f and h are radically changed compared with the preceding illustrations. In addition, the ball of the fifth toe does not contact the ground, as it does in a right-angled ankle joint. The remaining metatarsal heads are more heavily loaded because of the reduced area of distribution for the compressive forces.[14] The forefoot now holds the major part of the load. The force under the heel is further reduced.

Figures 2 through 4 illustrate the significance of the plantarflexed position of the ankle joint alone and ignore conditions caused by footwear. With a plantarflexed foot or a right-angled position in the ankle, the reaction forces are marked vertically (like A) and are supposed to have the same centers of action under the forefoot and the heel. The point of action under the forefoot is the head of the first metatarsal (the toes are assumed not to be loaded). The graphic analysis shows that the load under the forefoot, in the illustrated plantarflexed position, is about twice the load in a plantigrade position. Correspondingly, the load under the heel is reduced.

With high-heeled shoes, the angle in the ankle joint remains as if the foot were at push-off (at the end of the stance phase) (Fig. 5). The functional length of the forefoot (the distance between the line of action of forces A and F) in the transverse plane is reduced, whereas the functional length of the heel in the same plane is increased. Thus the forefoot must carry more load and the heel less load than usual. In addition, the heel seat (the carrying surface under the anatomical heel) is situated at a slight angle downward and forward compared with the horizontal plane, resulting in a less favorable orientation of

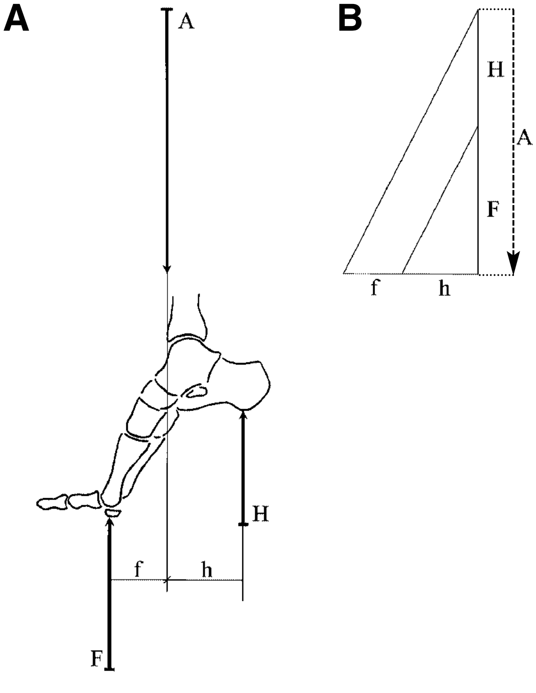

Figure 4. A, The forces under the forefoot (F) and heel (H) and the force of gravity (A) acting on the foot when standing and wearing high-heeled shoes with a horizontal heel seat. System: Whole body. B, Supporting illustration to determine F and H. Note that f and h represent moment arms.

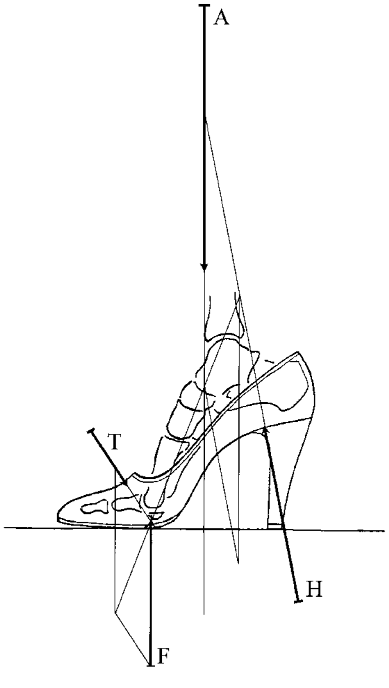

Figure 5. The forces under the forefoot (F) and heel (H) and the force of gravity (A) acting on the foot when wearing high-heeled shoes with an inclined heel seat and toe box (T). A graphic quantitative construction is included with the action force A as the only known vector and four lines of application with known directions. System: Whole body.

the support. The system (foot and whole body) is being attacked by four different forces. For one force (A), the line of action, direction, and magnitude are known. For the other three forces (F, H, and T [toe box]), lines of action and directions are assumed. Orientations and positions of forces H and T depend on the shape of the foot, the shoe, and probably the material used in the shoe. The interface forces between the foot and the shoe should have an even distribution in the two areas regarded as points of application for forces H and T. The force F under the ball of the foot is directed vertically and upward as a sheer counterforce to A. Force H is directed at an oblique angle, pushing the foot up and forward. H is marked at 90° to the oblique surface of support, traversing a point in the heel seat corresponding to the resultant reaction forces in this region (slightly anterior to force H in Figs. 2–4). To prevent the foot from sliding or being pushed forward, the shoe upper must act with a force component T directed backward. Forces H and T may be represented by vertical and horizontal components. The horizontal force components of H and T must be of equal magnitude and opposite directions. The vertical component of T leads to an increase in force F (increased load).

The magnitudes of F, H, and T can be estimated graphically because their lines and directions of action are known, force A is known, and the system is in equilibrium. The parallelogram law of addition of two and two forces is used to determine the magnitude of the three unknown forces.

Figure 6A illustrates how the forces can act on the foot when the foot is in a shoe with moderate heel height and a horizontal heel seat. Some elevation of the shoe heel will give the waist of the shoe (part of the shoe sole between heel and ball point) an arched shape that partly pursues the longitudinal arch of the foot. This invites a loading response to occur under the longitudinal arch. A "good shoe" and insoles are supposed to give support under the midfoot, more specifically under the central part of the longitudinal arch. This should reduce the load under the forefoot and the heel. These interface forces are difficult to measure and are studied with the aid of graphic analysis. The condition of forces is similar to the situation in Figure 3, where the reaction forces under the heel and the ball of the foot are parallel to the load, but in addition the carrying gelenk force G acts under the arch of the midfoot, and T acts from the shoe upper.

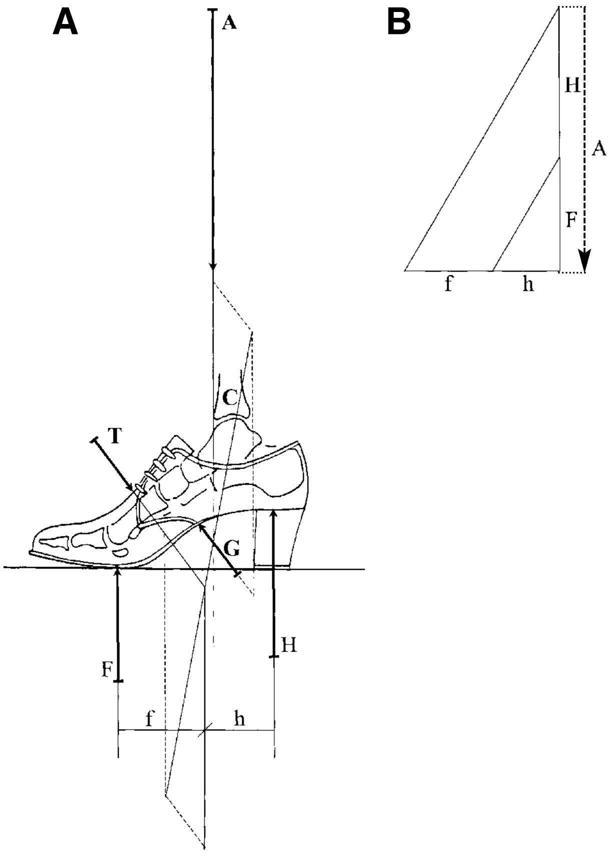

Figure 6. A, The forces under the forefoot (F), heel (H), gelenk (G), and toe box (T) and the force of gravity (A) acting on the foot when wearing shoes with moderate heel height, a horizontal heel seat, and support under the midfoot. System: Whole body. B, Supporting illustration to determine F and H. Note that f and h represent moment arms; C, common line of action.

The magnitude of force G is assumed to be known. Force G can be divided into horizontal and vertical components. The horizontal component tends to push the foot forward in the shoe. The shoe upper is firmly laced around the instep and prevents forward sliding by means of force T. The lines of action of G and T are parallel and are placed side by side. To enable the horizontal components of force to neutralize each other, the forces must be of opposite directions and of the same magnitude. The vertical components are also of the same magnitude and opposite directions. The moment of rotation formed by the couple of forces G and T results in additional load under the ball of the foot, whereas the corresponding force H is moderately reduced (compare Fig. 3).

The main idea behind this graphic construction is to limit the number of unknown forces to determine the forces now being studied. As all force vectors acting on the system keep the body in balance, the result must be zero. For example, the resultant forces of A and G must control the resultant forces of F, H, and T.

Thus the two resultant forces must be of equal magnitude and of opposite directions, and they must have a common line of action (C) to keep the system in static equilibrium. This line of action and the magnitude of both resultant forces can be determined when constructing a parallelogram put together by forces A and G (known magnitudes and action lines).

It is possible to locate the common intersection point of resultant line C, force T, and resultant force F + H by extending the action lines of C and T until they intersect. The action lines of T and resultant force F + H and the magnitude of C are known. By means of constructing a new parallelogram between resultant line C and the action line of force T, the sum of forces F + H parallel to forces F and H can be determined graphically. The couple of forces A and F + H creates a countermoment to the couple of forces G and T. Finally, the sum F + H is distributed between the ball of the foot and the heel (Fig. 6B).

G and T as a couple of forces represent a special case. The two forces must be neither of the same magnitude nor parallel. The only requirement is that their horizontal components must be of equal magnitude when no other horizontal forces are applied to the system. If the lacing puts T proximal to G, the result is a reduced F and an increased H (contrary to the figure), even if T still is pressing the forefoot in a plantar direction.

Discussion

Many people have foot pain that seems related to their footwear. The present graphic analyses of principle document that an increase in the heel height of the shoe may produce increased mechanical stress under the forefoot. The main cause of this event is that the moment arms (f and h) of the forces under the forefoot (F) and heel (H), respectively, are changing with the heel height of the shoe when the position of the weight line remains unaltered in relation to the axis of the ankle joint. This 2-D scenario from standing at ease or midstance during gait represents only an instant, and the model is thought to be adequate and representative of events that occur during human gait.

Sketches of principle made from simplified and explanatory geometric and mechanical reflections form the basis for the theoretical approach used in the presented graphic method. The model restricts and formalizes the problem to a discussion of mechanical issues by constructing several suppositions, including proposed assumptions, to permit a basis of comparison for the various situations. The model deals with parts of the whole and visualizes changed forces and moments within a complex picture. Nevertheless, with background knowledge and use of the presented elementary mechanical and geometric principles, physicians can apply the graphic method as a practical and helpful tool to elucidate various clinical orthopedic problems and to facilitate the interpretation of technical and biomechanical parameters used in gait and movement analysis.

The graphic analyses of mechanical consequences of the location and magnitude of compressive forces under the planta when changing the position of the ankle joint are meant only as analyses of principle, where the qualitative aspects are emphasized. The quantitative significance will vary in practice, depending on anthropometric measurements. The magnitude of forces can be compared in a numeric analysis on the basis of the relative proportions, ie, percentages.

The results of the present theoretical study agree with those of many scientists who find that increased heel height leads to increased load under the forefoot.[2, 4-8] However, none of the authors explained their results using a graphic illustration. Snow et al[6] and Nyska et al[5] found that maximum load under the forefoot increased and occurred at an earlier stage in the gait cycle as the heel height of the shoe was increased. Snow and Williams[7] found that vertical forces and anteroposterior forces under the foot increase during high-heeled gait. Schwartz et al[15] reported increased resultant compressive forces under the foot in high-heeled gait. Primarily, the force under the forefoot increased, and the reduction in force beneath the heel was evident with heel heights of 50 mm or more. Corrigan et al[14] measured the load under the forefoot at different heel heights attached directly under the anatomical heel. No change in total load under the forefoot was found, but the load was shifted toward the medial part of the forefoot, and the area of contact was reduced. This resulted in increased compressive stress under the forefoot (the local compressive force on the defined surface) with increasing heel height.

The present analyses of principle do not account for the fact that the configuration of the foot changes slightly with different ankle positions and load conditions. The tightening of the plantar aponeurosis also means that the toes are pressing the substratum, even without muscular activity,[16] thus indicating a minor distal displacement of the force under the forefoot and more load under the balls of the toes. The point of application of the force under the forefoot remains unchanged and is considered only in the sagittal plane of the foot.

The 2-D graphic analysis in the sagittal plane of an idealized model of the foot does not consider shear forces between the shoe and the foot. The magnitude of shear forces is difficult to assume and should be illustrated to increase the accuracy of the model. Hosein and Lord[17] measured shear stress and compressive stress between the planta and the shoe. They demonstrated a scatter between the two parameters, and the resultant force did not reflect force plate measurements. The authors concluded that the shoe upper must have a considerable and significant influence on the conditions of forces under the foot.

The main functions of the shoe upper are to keep the foot in place on the insole and to prevent forward sliding. In making the shoe clutch all of the midfoot and the lower part of the leg, the shoe upper can create horizontally positioned and backward-directed forces against the upper part of the foot and the distal part of the leg, without the foot being pressed further down against the substratum. If a person must use footwear with high heels (eg, in equinus and leg-length inequality), the shaft of the shoe should be extended and firmly laced.

The load under the foot also depends on the shape of other parts of the shoe, the characteristics of forces arising between the foot and the shoe, the period of load, and a shift of phases in the gait cycle.[5-7, 18, 19] The shoe shape should allow the lines of action of the supporting forces under the heel to be as vertical as possible, as these force components carry a major part of the body weight without pressing the foot forward in the shoe. A shoe with support under the midfoot could benefit from low heels to prevent the foot from being pressed against the shoe upper. When using an orthopedic inlay, the supporting forces under the sole of the foot are distributed over a wider area, reducing partial compressive stress.

Patients with metatarsalgia may benefit from avoiding high-heeled shoes. However, if the patient also has painful heels, augmented heel height might reduce compressive pain under the heel. Plantarflexion of the ankle joint in shoes with high heels is accompanied by dorsiflexion of the toes. This implies that the plantar aponeurosis is tightened, pulling the calcaneus forward and the distal part of the metatarsals backward, with a major effect on the first ray (windlass mechanism).[20] The intensified stretch in the plantar aponeurosis may result in a heavier load in the insertion fibers between the aponeurosis and the calcaneus, causing tendinitis and possibly a heel spur in the area of origin. The relation between compressive and tensile pain in this zone and a connection with the windlass mechanism and the heel height of the shoe is uncertain.

Muscular forces are not included in the method presented. However, it is clear that force A (Figs. 2–4) is inviting the truncus to fall forward about the ankle joint, and the musculus triceps surae must be active to prevent this. With the leg vertical, the lever arm of the musculus triceps will increase with the heel height, and, correspondingly, the need for force in the muscle to prevent a “fall” will diminish. The functional length of the forefoot is shortened by increasing the heel height, and the travel path of the reaction force forward during stance is reduced, resulting in decreased dorsiflexion moment in the ankle joint. Consequently, it is recommended that patients with a painful Achilles tendon temporarily use elevated shoe heels to unburden the Achilles.[3] In addition, the muscle fibers will work in a slightly different direction relative to the insertion on the calcaneus, resulting in a redistribution of loaded fibers.

During normal gait, the reaction force from the substratum, relative to the shoe and to the foot, is moving from the posterior border of the heel to the ball of the foot and the toes.[21, 22] In addition, a human being never stands completely still, with the gravity from above extending through a single point. The body’s center of gravity oscillates back and forth and from side to side. The movement of the center of gravity means that the point of application of the reaction force under the foot, the center of pressure, is continually displaced somewhat with respect to the line of gravity.[23] However, there is general agreement that the line of gravity is falling ahead of the ankle joint in a normal standing position.[7, 12, 24-27] Measurements of the distance between the gravity’s line of action and the ankle axis (moment arm) vary from study to study, perhaps because of the pendulum movement of the body.[23, 27] In dynamic situations, this distance will vary considerably.

Electromyographic measurements have established that the musculus triceps surae is more active when using high heels.[24] This may indicate that high heels in these cases resulted in a shift of the line of gravity even further forward than what would correspond to the increased horizontal length in the heel (the lever arm of musculus triceps). However, the increased activity may also be explained by the muscle’s length-tension diagram, as the muscle needs to create more force by increased contraction to maintain steady state when the length is reduced. The horizontal (functional) length of the forefoot is reduced, but this does not result in a shift of the gravity’s action line *per se*. The forward shifting of the weight line could be brought about by the individual’s trying to avoid loading of the insole under the heel (the heel seat), as a load here would result in a tendency to slide down and create pressure on the distal and upper part of the foot. Another explanation may be that the posture of the body changes with the angle of the ankle joint and that angles and moments in different joints of the body depend on the position of the ankle. With high-heeled shoes, the balance in the ankle complex (talocrural and subtalar joints) usually requires more muscular activity to stabilize the joints. Adrian and Karpovich[28] noted foot instability when comparing use of high-heeled shoes with the barefoot condition, and other researchers[24, 29, 30] have found increased muscular activity.

In the present graphic analyses, action lines of unknown forces have been selected. The gravitational force is regarded as a vector with a known position, direction, and magnitude. Lines of action of the other forces attacking the foot as a system are found by relying on experience and logical deduction. Measurements taken by pressure sensors in footwear[12] have also been used as a guideline. In a motion laboratory with force plates or mats for measuring pressure, it is possible to determine the magnitude of the reaction force and to raise the value of analysis from the general theoretical level to the practical individual level.

The present model represents a graphic solution to a mechanical problem, which can be checked through an analytic approach. The starting point is static equilibrium on the assumption that $\sum F = 0$ and $\sum M = 0$. By simple logic, the analysis of principle forms a basic understanding that can help us interpret and understand advanced measurement parameters from force plates and cameras in a motion laboratory, including kinetic and kinematic information with moments, forces, and angles in single joints of the body. The graphic analysis model is a practical and versatile tool that is easy to use in the clinic, requiring some knowledge of geometric construction and plain mechanics. Comparing results from more sophisticated laboratories with the principal findings in the previous examples, we find that the 2-D analysis offers a unique and reliable method to investigate geometric relations in complicated situations.

Conclusion

The graphic analysis of principle method demonstrated that load under the forefoot increases with the heel height of the shoe, whereas load under the heel decreases. With a high heel, load under the midfoot leads to an increased compressive load under the forefoot. This forms the basis for the assumption that patients with metatarsalgia due to increased compressive forces should use footwear with low heels. With an elevated height of the shoe heel, the lacing should contribute with a counterforce against the instep of the foot and the lower part of the leg.

The analysis does not call for much equipment, but it has some limitations because of the presupposed simplifications. The graphic model addresses basic principles only and accounts for very few individual variations. If information about the individual patient is desirable, measurements must be performed using force plates or other advanced (eg, pedobarographic) methods. In addition, compression and shear sensors and kinematic parameters should be included. The presented analysis of principle primarily serves as a practical guide, by use of logical sequences of thinking, to predict variations in the compressive force or stress under the sole of the foot at different heel heights, but it can be extended to more general use to help explain various orthopedic problems.

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