Effects of Simulated Genu Valgum and Genu Varum on Ground Reaction Forces and Subtalar Joint Function During Gait

Article *in* Journal of the American Podiatric Medical Association · November 2005

DOI: 10.7547/0950531 · Source: PubMed

Kevin Arthur Kirby
California School of Podiatric Medicine

Friso Hagman
Vrije Universiteit Brussel

Effects of Simulated Genu Valgum and Genu Varum on Ground Reaction Forces and Subtalar Joint Function During Gait

Bart Van Gheluwe, DrSc*
Kevin A. Kirby, DPM†
Friso Hagman, DrSc*

The mechanical effects of genu valgum and varum deformities on the subtalar joint were investigated. First, a theoretical model of the forces within the foot and lower extremity during relaxed bipedal stance was developed predicting the rotational effect on the subtalar joint due to genu valgum and varum deformities. Second, a kinetic gait study was performed involving 15 subjects who walked with simulated genu valgum and genu varum over a force plate and a plantar pressure mat to determine the changes in the ground reaction force vector within the frontal plane and the changes in the center-of-pressure location on the plantar foot. These results predicted that a genu varum deformity would tend to cause a subtalar pronation moment to increase or a supination moment to decrease during the contact and propulsion phases of walking. With genu valgum, it was determined that during the contact phase a subtalar pronation moment would increase, whereas in the early propulsive phase, a subtalar supination moment would increase or a pronation moment would decrease. However, the current inability to track the spatial position of the subtalar joint axis makes it difficult to determine the absolute direction and magnitudes of the subtalar joint moments. (J Am Podiatr Med Assoc 95(6): 531-541, 2005)

Genu valgum and genu varum are well-known structural abnormalities of the lower extremity. Genu valgum deformity, commonly called "knock knee," involves a valgus angulation of the tibia in which the feet are separated more than the knees during standing. Genu varum deformity, commonly called "bowleg," involves a varus angulation of the tibia in which the knees are separated more than the feet during standing.

The conditions of genu valgum and genu varum have been recognized for many years by clinicians, especially with respect to lower-limb dysfunctions or injuries.[1-3] Genu valgum deformity has been shown to have an adverse effect on the lower-extremity kinematics of gait in children,[1] may be associated with athletic injuries of the lower extremity,[2] and has been linked to an increased risk of overuse injuries in military recruits in basic training.[3] Genu varum and genu valgum deformities will also increase the joint forces at the medial and lateral compartments of the knee, respectively, which can lead to osteoarthritis of the knee.[4] Osteoarthritis in the medial and lateral compartments of the knee has been successfully treated with valgus and varus in-shoe wedges, respectively.[5] In addition, research[6] has shown that both deformities may affect the location of the center of pressure and the mechanical control of balance during single-limb balance.

*Laboratory of Biomechanics, Vrije Universiteit Brussel, Brussels, Belgium.

†Department of Applied Biomechanics, California School of Podiatric Medicine at Samuel Merritt College, Oakland; private practice, Sacramento, CA.

Corresponding author: Bart Van Gheluwe, DrSc, Laboratory of Biomechanics, Vrije Universiteit Brussel, Fac LK, Pleinlaan 2, 1050 Brussels, Belgium.

However, only a few studies describe the specific effects of genu valgum and genu varum deformities on foot function. Sgarlato[7] stated that genu valgum deformity was associated with abnormal subtalar joint (STJ) pronation and that a partially compensating pronation abnormality of the foot may evert not only the calcaneus but also the tibia. Valmassy[8] stated that increased angles of genu valgum deformity in the child shift the overall body weight to the medial aspect of the foot, which increases the tendency toward abnormal foot pronation.

Contrary to the prevailing belief in podiatric medicine that genu valgum deformity causes abnormal foot pronation, Kirby[9] suggested that it may have a supination influence on the foot. Kirby reasoned that because the vector of the ground reaction force (GRF) within the frontal plane is angulated more medially than normal, the STJ supination moment on the foot will increase through an effective increase in the length of the STJ supination moment arm. Kirby claimed that the clinical evidence for this change in frontal plane angulation of the GRF vector in patients with genu valgum deformity was the characteristic inverted heel counter wear pattern of the patients' shoe uppers. In effect, the medially directed GRF vector pushes the shoe sole medially, relative to the foot, with each step. This same force also was noted to cause the foot to slide laterally inside the shoe, deforming the upper of the shoe over time.

With the lack of specific scientific research on the subject, suggestions of the functional consequences of genu varum and genu valgum deformities for foot function have been only speculative to date. If genu varum and valgum deformities alter the nature of the GRF, as some authors have noted, then this would significantly affect the mechanical function of the foot. If, however, the GRF is changed because of the frontal plane angulation of the knee, then this would indicate that any mechanically based therapy for the foot, such as foot orthoses or shoe modifications, should be appropriately modified to account for these differences in GRF acting on the plantar foot.

The goals of our study were twofold. First, a theoretical model for bipedal stance was developed to determine how varus and valgus knees, compared with knees with normal alignment, affect the direction of GRF and the resulting moments of force around the STJ in a static situation. This simplified model of bipedal stance was necessary to better illustrate the internal forces that exist within the foot and lower extremity during a weightbearing situation so that the more complicated and dynamic condition of walking can be more easily understood. In addition, an evaluation of a static bipedal model of genu valgum and varum deformities was appropriate because the clinical evaluation of frontal plane deformities of the knee is mostly performed in static stance and the only literature references to the genu valgum deformities are theoretical evaluations in static stance situations.[1, 2]

The second goal of our study was to investigate the changes in GRF vectors and center of pressure (ie, center of force) that occur when subjects walk with simulated genu valgum and genu varum deformities in order to estimate the resulting dynamic effects on the STJ. By noting these changes in GRF vectors and centers of pressure that were caused by alterations in the base of gait of the experimental subjects, it was hoped that clinical inferences may be made in patients with frontal plane angulation deformities of the knee to improve the understanding of the biomechanical effect of frontal plane knee deformities on foot function.

Theoretical Effect of GRF on STJ Moments in Relaxed Bipedal Stance

Before studying the effect of GRF on STJ moments due to varum or valgum knee deformities in a dynamic condition such as walking, it is important to first consider the static situation of bipedal standing to simplify the mechanical analysis. To determine the forces that act on a structure, it is useful to construct a free-body diagram in which the forces and moments that act on the structure are analyzed by replacing the mechanical effects of its surroundings with corresponding forces.[10] To this end, a free-body diagram was developed to estimate the magnitude and direction of the frontal plane GRF vector that occurs in relaxed bipedal stance. First, normal knee and ankle alignment was analyzed (Fig. 1). To simplify the model, the thigh, shank, and foot segments were assumed to be rigidly connected to each other. In addition, the hip joints were assumed to be completely relaxed, with no muscular contractile activity across the hip joint; only the contact forces acting at the hip joint were considered.

The results of the calculations state that the GRF vector that acts on the plantar aspect of the foot should point toward the hip joint within an error of 2° (Appendix 1). This is true for relaxed stance, in which the normal distance between the feet is not more than 50 cm for a corresponding hip height of 100 cm. A valgum or varum misalignment of the knee does not alter this result because the equilibrium equations remain unaffected by the anatomical shape of the leg (Fig. 2). However, because the alignment of the foot relative to the hip within the frontal plane has been altered by the difference in frontal plane

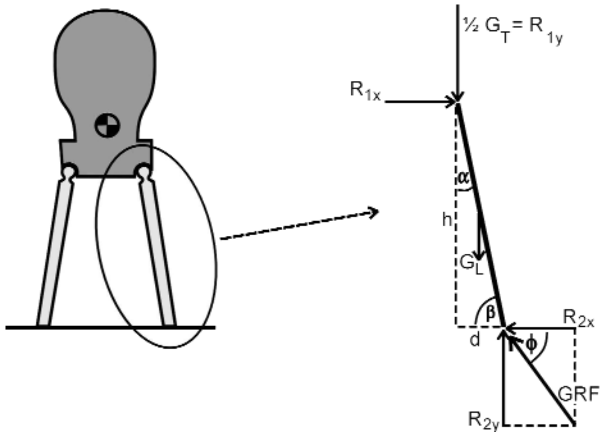

Figure 1. The diagram on the left is of a model of an individual standing with a wide base of gait. On the right is a free-body diagram analyzing all of the forces that act on one leg of the model. The femur, leg, and foot have all been combined as one rigid segment, and the muscular influences at the hip have been eliminated to simplify the model. The calculations given in Appendix 1 determine that the ground reaction force (GRF) vector will point toward the hip joint if no muscular influence at the hip is present during relaxed bipedal stance.

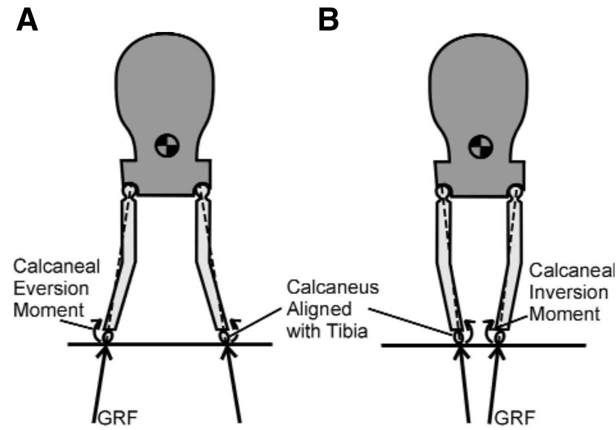

Figure 2. A, In relaxed bipedal stance with genu valgum deformity and the calcaneus aligned with the tibia, there will be a slight pronation moment acting on the calcaneus due to the ground reaction force (GRF) vector being lateral to the subtalar joint axis. B, With a genu varum deformity and the calcaneus aligned with the tibia, there will be a slight supination moment acting on the calcaneus due to the GRF vector being medial to the subtalar joint axis.

knee alignment, the angle of the GRF vector acting on the plantar foot in the static bipedal stance will be directed laterally with a genu valgum deformity and medially with a genu varum deformity.

In our simplified model in relaxed bipedal stance, the resulting rotational forces (ie, moments) that act across the STJ will tend to cause opposite effects on the STJ in genu valgum and genu varum deformities. If we assume that the calcaneus is perfectly aligned with the tibia and that the STJ axis is directly in the center of these two segments, the GRF will exert a slight STJ pronation moment with a genu valgum deformity and a slight STJ supination moment with a genu varum deformity (Fig. 2).

However, if the calcaneus is assumed to be vertical to the ground, an opposite rotational effect on the STJ will be produced by the effects of the GRF (Fig. 3). In this condition, the mechanical effect that the GRF has on the STJ now depends on whether the STJ is medial or lateral with respect to the hip joint and not necessarily on the varum or valgus position of the knees. In other words, a genu valgum deformity with the STJ axis lateral to the hips will create a slight STJ supination moment (Fig. 3A) and a genu varum deformity with the STJ axis medial to the hips will create a slight STJ pronation moment (Fig. 3B). Therefore, in the condition of relaxed bipedal stance, in which the GRF vector is directed toward the ipsilateral hip joint, the rotational effect of the GRF will depend on the alignment of the rearfoot relative to the ground and its mediolateral position relative to the ipsilateral hip.

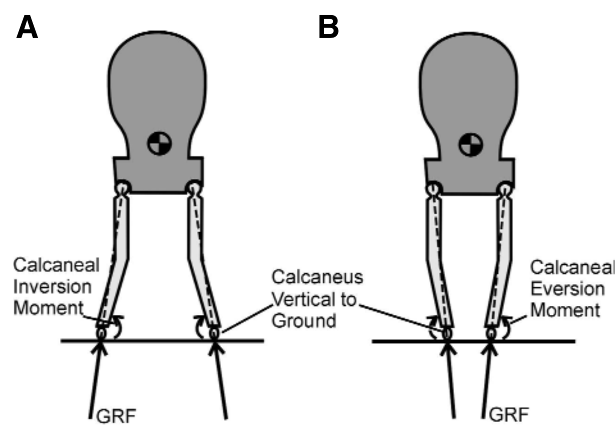

Figure 3. A, In relaxed bipedal stance with genu valgum deformity and the calcaneus vertical to the ground, there will be a slight supination moment acting on the calcaneus due to the ground reaction force (GRF) vector being medial to the subtalar joint axis. B, With a genu varum deformity and the calcaneus vertical to the ground, there will be a slight pronation moment acting on the calcaneus due to the GRF vector being lateral to the subtalar joint axis.

Experimental Assessment of STJ Moments Due to GRFs During Walking with Simulated Genu Valgum and Varum

In our study, the varum and valgum malalignments of the knee were simulated by instructing each subject to walk using four different types of gait patterns in a random order. A normal gait style (condition A) acted as a reference. The subjects also walked with a "scissors-style" gait pattern to increase the varus angulation of the lower extremity and to simulate genu varum deformity (condition B) and with a very wide base of gait to simulate genu valgum deformity (condition C). Finally, subjects also walked with a very wide base of gait with a knock-knee gait pattern to simulate genu valgum deformity in another manner (condition D) (Fig. 4).

To measure GRFs and their center of pressure, the subjects walked across a force plate (Kistler, Zurich, Switzerland) and a pressure plate (Footscan; RSscan International, Olen, Belgium) that were built into the walkway. The pressure plate was not put on top of the force plate because this setup proved to significantly affect the accuracy of GRF measurements using the force plate. Therefore, the pressure plate was put in front of the force plate so that force plate and pressure plate measurements were made on consecutive steps during the walking trials.

A total of 15 male subjects aged 18 to 25 years were measured. None of the subjects had a history of neuromuscular disorders or previous significant traumatic injuries of the lower limbs, and none had complaints of injury or pain in the lower extremities at the time of the study. Written consent was obtained from all participants.

The subjects were asked to walk at their preferred speed until a minimum of three acceptable trials of the left and right limbs were recorded. A trial was accepted when the force and pressure recordings were free of artifacts and visually resembled one another closely from trial to trial. The sampling frequency of the force plate and the pressure plate was 500 Hz. Calculation of the location of the center of pressure was taken from the pressure plate because the pressure plate enabled calculation of the lateral displacement of the center-of-pressure path relative to the inertial axis of the foot. The inertial axis of the foot is defined as the line that connects the center of weightbearing pressure of the heel and the forefoot in the hypothetical case in which the plantar pressure is equally distributed over the whole foot. This pressure-oriented definition of center-of-pressure displacement was preferred to the geometric estimation of the lateral foot or another midline reference of the foot because the center-of-pressure displacement was more consistent between trials.

The force measurements and lateral deviation of the center of pressure were measured at two distinct times during the stance phase: at the instant of the first peak of vertical GRF (during heel loading) and at the instant of the second peak of vertical GRF (during early propulsion). The separate locations of the force plate and the pressure plate on the walking platform in the laboratory necessitated that the GRF vector and center-of-pressure measurements come from separate steps during each walking trial, which may be viewed as a potential limitation of the study. However, because the results of the study rely on statistical testing of the mean value of several trials, we believed that this potential limitation would not significantly affect the experimental results.

The four different walking conditions were compared with each other using a repeated analysis of variance (ANOVA) design. Subsequent *a posteriori* testing was performed to locate significant differences using paired *t*-testing with Bonferroni adjustment. Therefore, to retain a final .05 level of significance during the *a posteriori* testing, the ANOVA level of significance was set at .01. Correlation between the left and right sides was performed using the Pearson product moment correlation test (with a significance level of .05). All of the tests were allowed to be parametric because the data of all variables selected were proved to be normal according to Kolmogorov-Smirnov statistics. The statistical analyses were performed on the GRF variables that were thought to have a mechanical effect on the pronation and supination moments that act across the STJ axis. These variables were the mean peak vertical GRF component, the mean peak mediolateral GRF component, and the lateral displacement of the center of pressure relative to the inertial axis of the foot.

Results

Because several correlation coefficients between the left and right feet proved to be significant, all subsequent statistical analyses were performed for each foot separately. A repeated ANOVA was applied to check for significant differences among the four walking conditions. It was noted that changes in the mean peak vertical GRF component, mean peak mediolateral GRF component, and center of pressure were very similar for both feet; thus the subsequent discussion of results combines the values for the left and right feet.

An analysis of the mean peak vertical GRF component during heel loading (ie, first peak) for

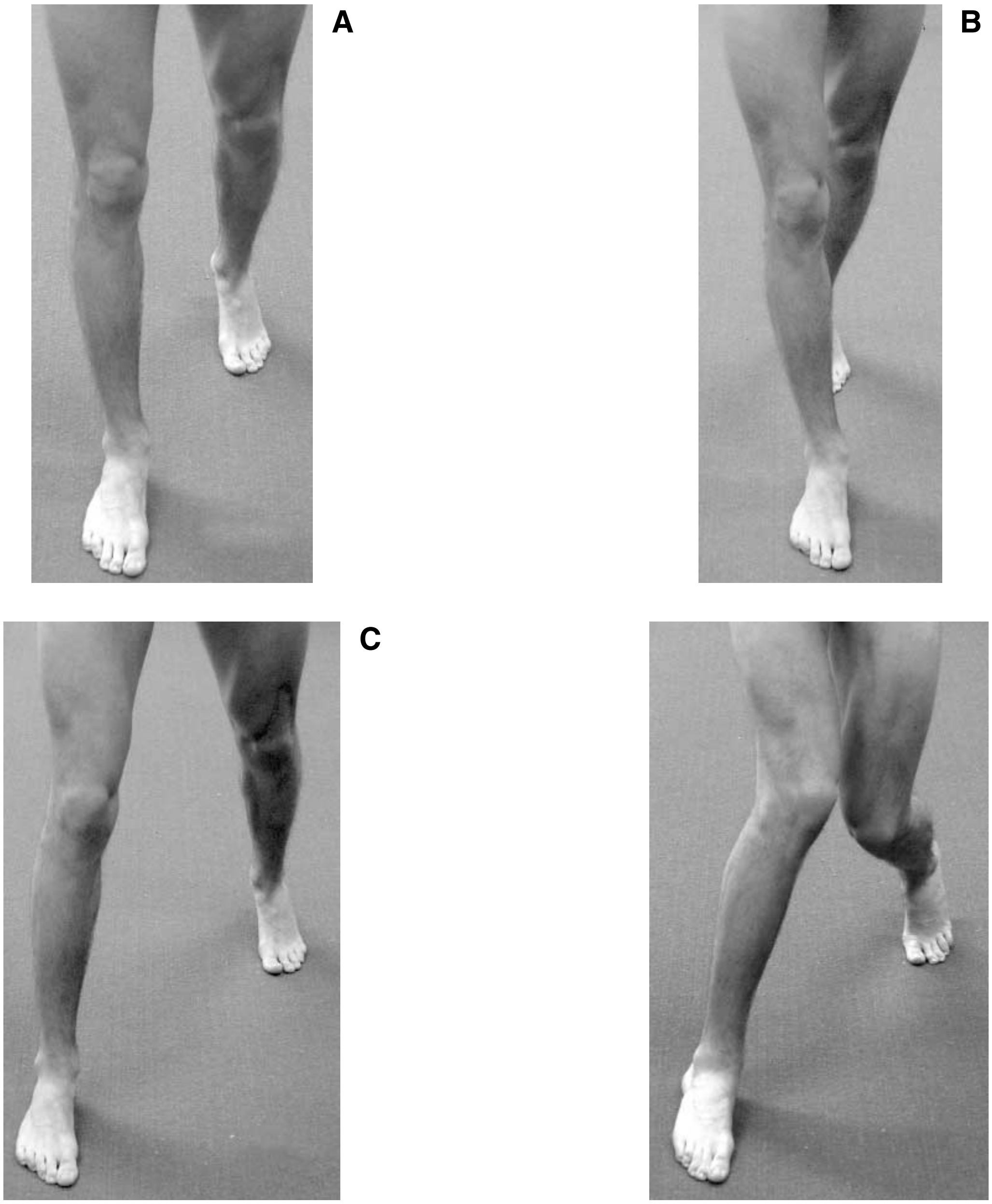

Figure 4. Each subject was asked to walk using four different gait patterns: normal gait (A); scissors gait, simulating genu varum deformity (B); wide base of gait, simulating genu valgum deformity (C); and wide base of gait with knock knee (D), also simulating genu valgum deformity. Subjects walked over a force plate and a pressure plate using these gait patterns.

the four walking conditions revealed a significant ANOVA (F_{left} = 7.56; F_{right} = 6.61; *df* = 3; P_{left} = .0003; P_{right} = .0008). *A posteriori* testing showed that when walking with a genu varum deformity (condition B), the mean peak vertical GRF component was not significantly different (P_{left} = .08; P_{right} = .56) from its value during normal gait (Fig. 5A). In the case of genu valgum deformity (condition C), the mean peak vertical GRF component was found to be larger compared with normal gait, although significantly only for the left side (P_{left} = .005; P_{right} = .16). However, in knock-knee walking (condition D), significant differences occurred for the left and right sides (P_{left} = .002; P_{right} = .002). During early propulsion (ie, second peak), the mean peak vertical GRF component was significantly different (F_{left} = 49.07; F_{right} = 57.15; *df* = 3;

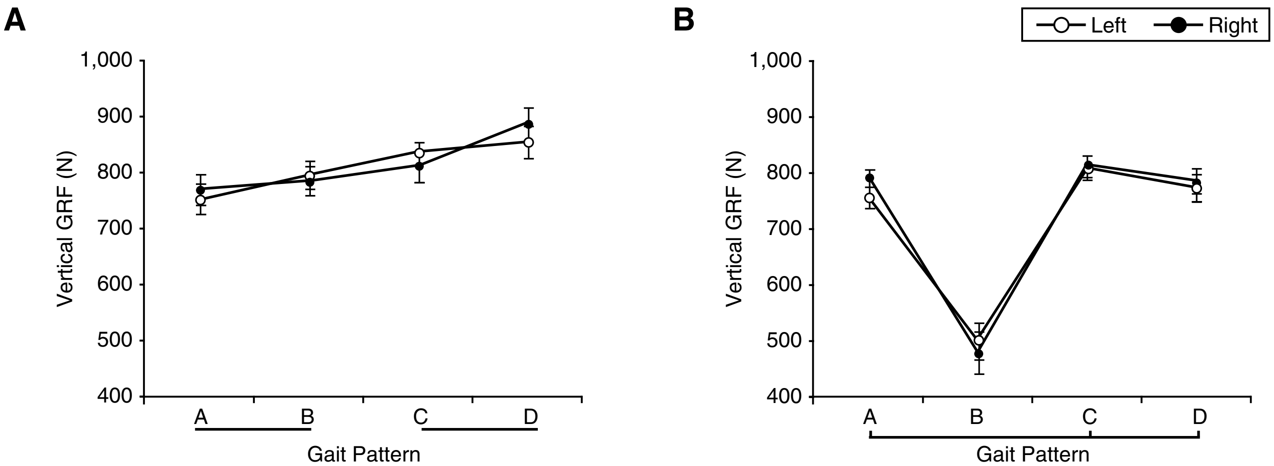

Figure 5. Mean vertical ground reaction forces (GRFs) for the four gait patterns during heel loading (A) and early propulsion (B). The connecting line under the gait patterns signifies the grouping of gait patterns with no significant differences. Error bars represent SE.

$P_{left} < .001$; $P_{right} < .001$), but only between normal gait and the genu varum condition ($P_{left} < .001$; $P_{right} < .001$) (Fig. 5B).

A posteriori analysis after a significant ANOVA ($F_{left} = 67.92$; $F_{right} = 98.07$; $df = 3$; $P_{left} < .001$; $P_{right} < .001$) of the mean peak mediolateral GRF values during heel loading showed that all conditions were significantly different from each other ($P < .001$ for all), except between the two genu valgum conditions (conditions C and D) ($P_{left} = .94$; $P_{right} = .88$) (Fig. 6A). The two genu valgum conditions produced the largest, medially directed mean peak mediolateral GRF component values, and the genu varum condition produced a reversal of the mean peak mediolateral GRF component to a lateral direction, although it was of a relatively small magnitude. Analysis of the mean peak mediolateral GRF component during propulsion was nearly identical to that during heel loading for all four walking conditions ($F_{left} = 93.01$; $F_{right} = 46.71$; $df = 3$; all $P < .001$) (Fig. 6B).

The position of the center of pressure relative to the inertial axis of the foot also changed for the four walking conditions (Fig. 7). The respective ANOVAs revealed significant differences, with $F_{left} = 56.20$ and $F_{right} = 30.99$ during heel loading and $F_{left} = 30.73$ and $F_{right} = 22.52$ during propulsion, all with $df = 3$ and

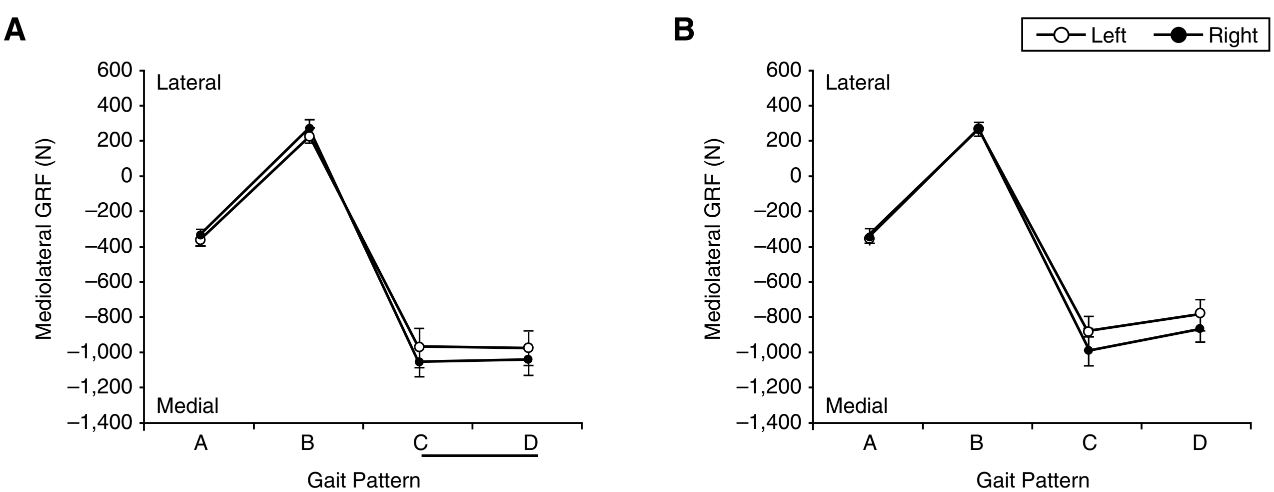

Figure 6. Mean mediolateral ground reaction forces (GRFs) for the different gait patterns during heel loading (A) and early propulsion (B). The connecting line under the gait patterns signifies the grouping of gait patterns with no significant differences. Error bars represent SE.

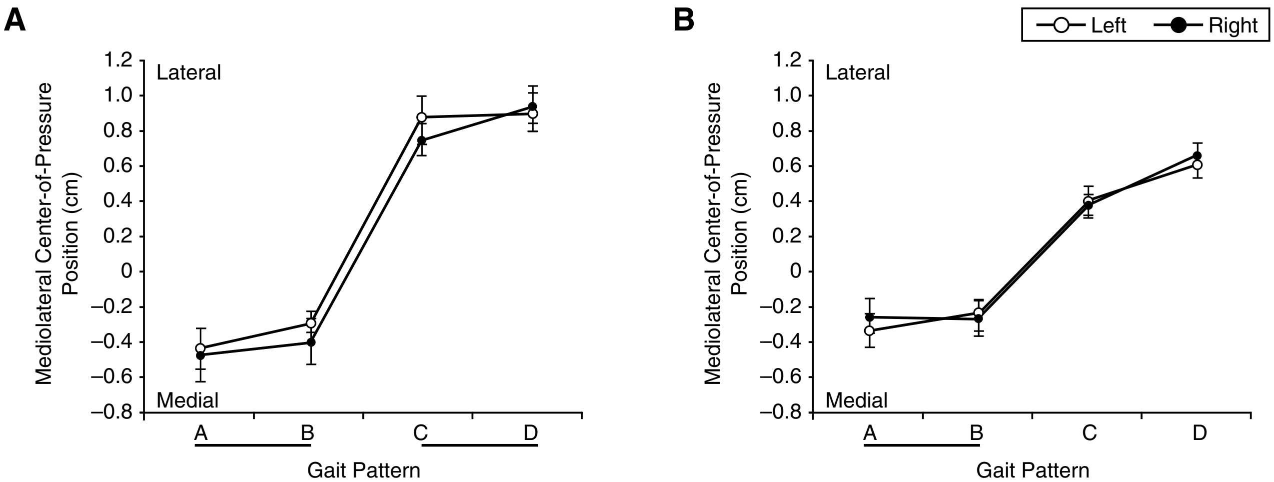

Figure 7. Mean mediolateral position of the center of pressure of the ground reaction forces for the different gait patterns during heel loading (A) and early propulsion (B). The connecting line under the gait patterns signifies the grouping of gait patterns with no significant differences. Error bars represent SE.

$P < .001$. Again, for heel loading and propulsion, relative to the normal condition, there was no significant shift of the center of pressure with the genu varum condition (P = .078–.549), but there was a significant lateral shift for the two genu valgum walking conditions ($P < .001$ for all). This lateral shift was greater for the heel loading peak (Fig. 7A) than for the propulsion peak (Fig. 7B). There was also a small but significant increase in lateral center-of-pressure position when condition D was compared with condition C, with and without knock knee (P = .02–.03), except in the left heel (P = .78).

By combining the force components mean peak vertical GRF and mean peak mediolateral GRF to produce a graphic representation of the angular slope of the resultant GRF vector measured by the force plate during the four walking conditions, the GRF vector orientation and position on the plantar foot is better appreciated (Fig. 8). With these GRF vectors oriented on a horizontal scale of their mediolateral positions on the plantar foot, the significant lateral shift in center-of-pressure position is apparent in the two genu valgum walking conditions. It is also evident that the normal and genu valgum walking conditions had the GRF vector oriented medially and that the genu varum condition had the GRF vector oriented laterally, although only slightly (Figs. 8 and 9).

Discussion

When attempting to determine the exact mechanical effects of GRF across the STJ axis, just as in any other situation in which the mechanical effect of a force relative to an axis of rotation is being analyzed, it is important to know the vital characteristics of the applied force and the axis of rotation. Regarding the force, it is imperative that the magnitude, point of application, line of action, and direction are known. For

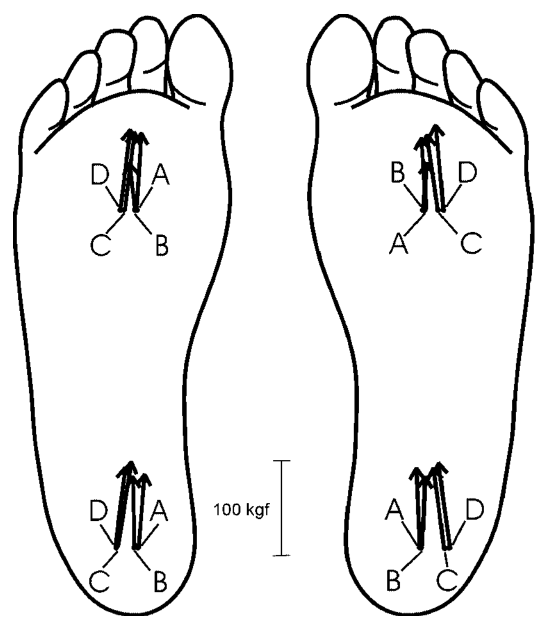

Figure 8. Diagrams of the magnitude and frontal plane angulation of the ground reaction force vector combined with the mediolateral position of its center of pressure for the different walking conditions A, B, C, and D. These are combined with an illustration of the plantar foot to demonstrate the approximate locations of the centers of pressure for the first and second ground reaction force peaks on the plantar foot.

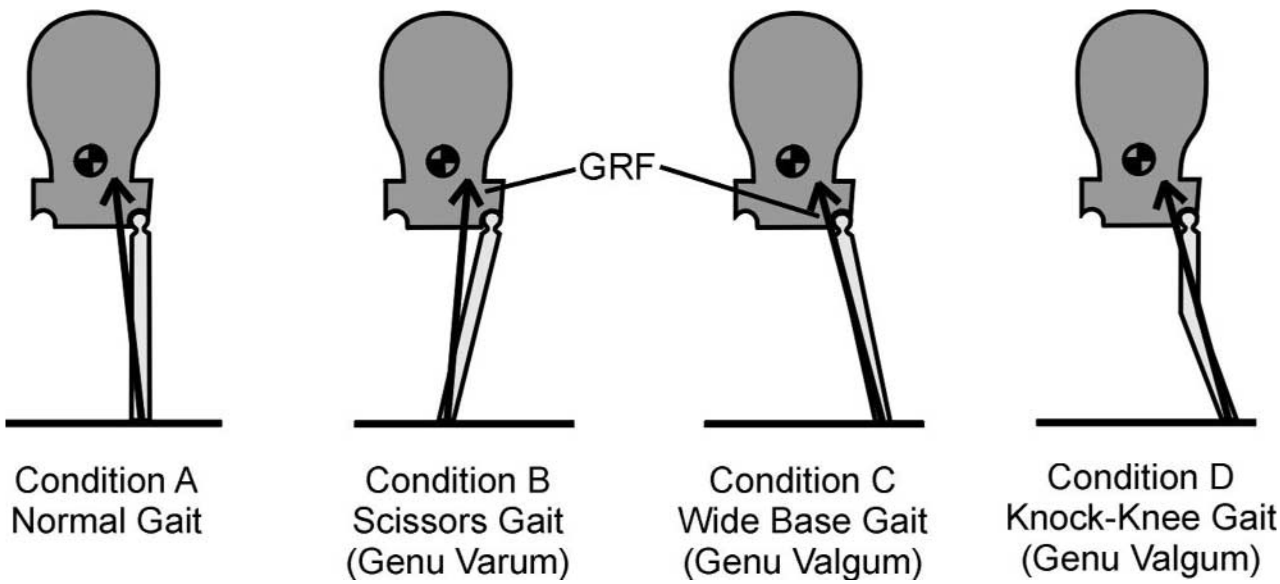

Figure 9. Models of walking conditions A through D used in this study depicting the orientation of the ground reaction force (GRF) vector within the frontal plane. In condition B (scissors gait), the GRF vector was directed laterally. However, in conditions A (normal gait), C (wide base of gait), and D (knock-knee gait), the GRF vector was directed medially.

the axis of rotation, its spatial location relative to the force must be known. Therefore, to precisely calculate the effects of GRF across the STJ axis during different walking conditions, the magnitude, point of application, line of action, and direction of GRF must first be determined, along with the precise spatial location of the STJ axis relative to the GRF vector.

In a static situation, as in relaxed bipedal stance, the characteristics of the GRF vector can be derived on theoretical grounds, without experimental data collection. However, even for the simple static condition of relaxed bipedal stance, it was demonstrated that the direction of the subtalar moments of force (ie, pronation moments *versus* supination moments) could not be precisely determined because they were directly dependent on the frontal plane alignment of the calcaneus, its mediolateral position under the ipsilateral hip, and the spatial location of the STJ axis.

In our experimental approach of the four walking conditions, the magnitude, point of application (center of pressure), direction, and line of action of the center of pressure of GRF were determined by the combined use of a force plate and a pressure plate. However, because the location of the STJ axis rotates and translates within space relative to the plantar foot during walking and other weightbearing activities,[9, 11] we could not precisely determine the actual magnitudes of the STJ pronation and supination moments that occurred during the different walking conditions. Although our experimental data cannot yield a precise determination of the absolute magnitudes of the STJ pronation and supination moments that result from GRF, the experiment does yield sufficient data to allow an approximation of the relative effects that changes in GRF vector direction and center-of-pressure position may have on the mechanics of the STJ with different walking conditions.

In the simulated genu varum walking condition (condition B), center-of-pressure position was not significantly altered, but the mean peak mediolateral GRF component was significantly altered, tending to cause a change in the GRF vector toward a more lateral direction (Figs. 6 and 8). This finding indicates that when the subject was asked to place the foot more medially than normal during walking to simulate a genu varum deformity, GRF became more laterally directed. The resulting laterally directed shearing force that acts on the plantar foot in the genu varum condition would tend to increase the STJ pronation moments, as normally present during heel loading, or decrease any STJ supination moment.

Both genu valgum conditions (conditions C and D) significantly influenced the center-of-pressure displacement and the vertical and mediolateral magnitudes of GRF. The center of pressure was shifted toward the lateral foot by 12 to 14 mm during heel loading and by 7 to 9 mm during propulsion (Figs. 6–8). This lateral shifting of the center of pressure on the plantar foot would tend to increase the STJ pronation moment or decrease the STJ supination moment. However, both genu valgum conditions also caused the mediolateral GRF vector to become more medially directed, which would tend to decrease the STJ pronation moment or increase the STJ supination moment.

Therefore, these two opposing STJ rotational effects seen in the genu valgum conditions made it difficult to predict the exact mechanical effect on the foot because the spatial location of the STJ axis could not be precisely determined. However, using generalized assumptions of the approximate spatial location of the STJ axis in normal feet allowed a fair estimation of the possible change in STJ moments that may occur from the simulated genu valgum deformity.

To estimate an approximate location of the STJ axis for discussion purposes, we used the mean values for the STJ axis location from previous studies by Manter[12] and Inman,[13] in which the angle of inclination of the STJ axis was determined to be 42°. For the feet used in our study, which averaged 28 cm long, this 42° inclination angle of the STJ axis made the approximate distance of the STJ axis from the central aspect of the plantar calcaneus 4 cm (Fig. 10). In addition, this same 42° inclination of the STJ axis made the approximate distance from the plantar second metatarsal head to the STJ axis 18 cm.

The values mentioned previously are only crude approximations of the average STJ axis spatial location in the feet of our subjects, because the technology does not currently exist to allow determination of

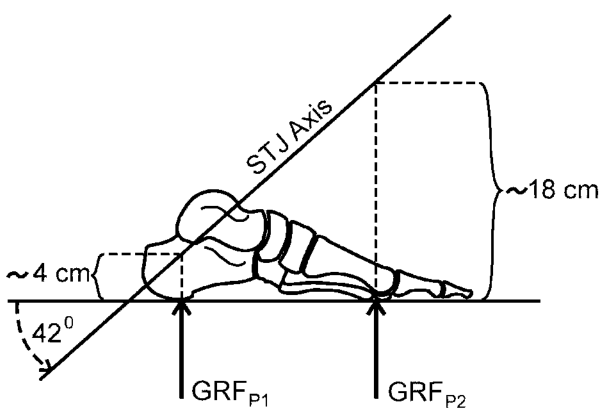

Figure 10. The angle of inclination of the subtalar joint (STJ) axis was approximated to be 42° in the subjects. As a result, the ground reaction force (GRF) at the first peak (GRF$_{P1}$) and that at the second peak (GRF$_{P2}$) gave different STJ vertical moment arm lengths. For GRF$_{P1}$, the STJ vertical moment arm length was approximated as 4 cm, and for GRF$_{P2}$, it was approximated as 18 cm.

the *in vivo* spatial location of the STJ axis during gait. However, to better appreciate the varying mechanical effects that the mean peak mediolateral GRF component has on the foot when different vertical moment arm lengths to the STJ occur, it is instructive to put numbers on these values in order to increase the clarity and meaning of discussion of these mechanical effects. It is also important to point out that the angulation of the STJ axis within the transverse plane does not affect the calculations of the differences in STJ moments between the experimental gait conditions in our study because we are only interested in the relative changes in frontal plane STJ moments that result from the changes in center-of-pressure position on the plantar foot and the changes in the magnitude of the mediolateral GRFs acting across the STJ axis.

Using these approximations of the moment arm lengths to the STJ axis, it was calculated that during heel loading, the effect of the center of pressure of the vertical GRF component (approximately 800 N) (Fig. 7A) moving laterally approximately 0.013 m created a much larger change in the STJ moments than did a simultaneous increase in the medial GRF component (approximately 70 N) acting approximately 0.04 m inferior to the STJ axis. The approximate amount of change due to a 0.013-m lateral displacement of the vertical GRF component would be 800 N × 0.013 m = 10.4 N·m in a pronation direction. The approximate change due to the 0.04-m supination moment arm from the change in the mediolateral component of GRF would be 70 N × 0.04 m = 2.8 N·m in a supination direction. Thus the shift in the mean peak vertical GRF component to a more lateral position produced a greater magnitude of STJ pronation moment than the STJ supination moment that was produced as a result of the increased magnitude of the medially directed mean peak mediolateral GRF component. As a result, at heel loading, it was predicted that the overall mechanical effect on the STJ of the simulated genu valgum walking pattern during heel loading was an increase in the STJ pronation moment or a decrease in the STJ supination moment.

During propulsion, however, the effects of GRF on the STJ axis were different from those seen during heel loading. First, the center of pressure was much more anterior on the foot during propulsion. In addition, because of the inclination angle of the STJ axis (Fig. 10), the distance from the STJ axis at the plantar forefoot was much greater than that at the plantar heel so that the STJ moment arm of the mediolateral GRF was much larger during propulsion (approximately 0.18 m). Therefore, during propulsion, the effect of the center of pressure of the vertical

GRF component (approximately 800 N) moving laterally approximately 0.008 m created an increase in the STJ pronation moment that was smaller than the simultaneous increase in STJ supination moment caused by an enlargement of the medially directed GRF component (approximately 60 N) acting approximately 0.18 m inferior to the STJ axis. The approximate amount of change due to a 0.008-m lateral displacement of the vertical GRF component would be 800 N × 0.008 m = 6.4 N•m in a pronation direction. The approximate change due to the mediolateral component of GRF acting across a 0.18-m moment arm would be 60 N × 0.18 m = 10.8 N•m in a supination direction. Thus, assuming that the STJ moment arm was 0.18 m, the change in magnitude of the medially directed mediolateral GRF component produced a larger STJ supination moment than the STJ pronation moment produced by the lateral shift in the vertical GRF position. As a result, during propulsion it was predicted that the overall mechanical effect on the STJ of the simulated genu valgum walking pattern was either an increase in the STJ supination moment or a decrease in the STJ pronation moment.

Different angulations of the STJ axis in the sagittal plane will significantly alter these results. An STJ with a higher-pitched axis will tend to have an increased STJ supination effect as a result of the medially directed mean peak mediolateral GRF component seen with genu valgum walking conditions than will an STJ that has a lower-pitched axis. Until researchers can precisely locate the STJ axis in space relative to the GRF vector during weightbearing activities, the exact magnitudes and directions of STJ rotational effects caused by changes in the GRF vector will be only approximations, at best.

In addition, the simulated genu valgum and genu varum gait patterns used by the subjects in our study are probably not representative of the true differences in the kinetic changes that occur in patients with actual genu valgum or genu varum deformities. The center-of-pressure position and the mean peak vertical GRF component and mean peak mediolateral GRF component values may be substantially different in actual patients with the deformities. Even slight changes in these values may tip the balance toward either increased STJ pronation moments or increased STJ supination moments during walking activities, especially during propulsion (second peak). Even with these recognized limitations of this study, we hope that this research will stimulate further interest in and investigation of how frontal plane angular deformities of the knee can alter the kinetic and kinematic function of the foot and lower extremity during walking and other weightbearing activities.

Conclusion

In relaxed stance, the effect of genu valgum or varum deformities depends largely on the frontal plane position of the calcaneus relative to the tibia as well as on its mediolateral position relative to the hip joint. During the dynamics of walking, the effect of a simulated genu varum condition has been estimated to cause either an increase in the STJ pronation moment or a decrease in the STJ supination moment during the heel loading and propulsion phases of gait. However, during a simulated genu valgum condition, it has been estimated that during heel loading the magnitude of the STJ pronation moment will be increased and that during propulsion the STJ supination moment will be increased or the STJ pronation moment will be decreased. Variations in the inclination angle of the STJ axis may significantly affect the magnitude and direction of the production of STJ moments, especially during propulsion. The current inability to precisely track the spatial location and orientation of the STJ axis during weightbearing activities makes it difficult to determine the direction and magnitude of the STJ moments that occur because of the action of GRF during different walking styles.

Appendix 1

Free-Body Analysis of the Lower Extremities During Relaxed Stance (with Aligned Knee and Subtalar Joint)

The equilibrium equations for the horizontal and vertical forces (x- and y-direction, respectively) acting on the leg (Fig. 1) can be formulated as follows:

(1) $R_{1x} = -R_{2x}$

(2) $R_{2y} = \frac{1}{2} G_T + G_L = G/2$

where R_1 is the joint reaction force at the hip joint, R_2 is the ground reaction force acting on the foot, G_L is the weight of the leg, G_T is the weight of the body without the legs, and G is the whole body weight.

Equilibrium for the respective moments of force across the center of force of the ground reaction force yields (assuming in good approximation that G_L acts at the middle of the leg and that $G_L = \frac{1}{7} G$)[14]

(3) $\frac{1}{2} G_T \cdot d + G_L \cdot d/2 = R_{1x} \cdot h$

or $R_{1x} = (G_T + G_L) \cdot d/2h = \frac{6}{14} G \tan \alpha$

The angle ϕ, expressing the frontal inclination of the ground reaction force with the vertical, using equations (1) and (2), can be expressed as follows:

$$\tan \phi = R_{2y}/R_{2x} = -7G/6(G \cdot \tan \alpha) = -\tfrac{7}{6} \cot \alpha$$
$$= -\tfrac{7}{6} \tan (90° - \alpha) = -\tfrac{7}{6} \tan \beta$$

The latter equation implies that both angles, ϕ and β, can be considered approximately equal within 2° during normal relaxed stance (assuming a hip height of approximately 100 cm combined with a corresponding foot base width not exceeding 50 cm). This implies that ground reaction forces are pointing toward the center of the hip joint. A wider stance will force the ground reaction force to be a few degrees steeper and to pass lateral to the hip center, which will introduce a slight increase in pronation moment around the subtalar joint.

References

1. Pretkiewicz-Abacjew E: Knock knee and the gait of six-year-old children. J Sports Med Phys Fitness **43:** 156, 2003.
2. Krivickas LS: Anatomical factors associated with overuse sports injuries. Sports Med **24:** 132, 1997.
3. Cowan DN, Jones BH, Frykman PN, et al: Lower limb morphology and risk of overuse injury among male infantry trainees. Med Sci Sports Exerc **28:** 945, 1996.
4. Maquet PGJ: *Biomechanics of the Knee*, Springer-Verlag, New York, 1984.
5. Wolfe SA, Brueckman F: Conservative treatment of genu valgus and varum with medial/lateral heel wedges. Indiana Med **84:** 614, 1991.
6. Nyland J, Smith S, Beickman K, et al: Frontal plane knee angle affects dynamic postural control strategy during unilateral stance. Med Sci Sports Exerc **34:** 1150, 2002.
7. Sgarlato TE (ed): *A Compendium of Podiatric Biomechanics*, p 381, California College of Podiatric Medicine, San Francisco, March 1971.
8. Valmassy RL: "Biomechanical Evaluation of the Child," in *Clinical Biomechanics of the Lower Extremities*, ed by RL Valmassy, p 243, CV Mosby, St Louis, 1996.
9. Kirby KA: *Foot and Lower Extremity Biomechanics II: Precision Intricast Newsletters, 1997-2002*, Precision Intricast Inc, Payson, AZ, 2002.
10. Nihat O, Nordin M: *Fundamentals of Biomechanics: Equilibrium, Motion and Deformation*, Van Nostrand Reinhold, New York, 1991.
11. Kirby KA: Subtalar joint axis location and rotational equilibrium theory of foot function. JAPMA **91:** 465, 2001.
12. Manter JT: Movements of the subtalar and transverse tarsal joints. Anat Rec **80:** 397, 1941.
13. Inman VT: *The Joints of the Ankle*, Williams & Wilkins, Baltimore, 1976.
14. Dempster WT: *Space Requirements of the Seated Operator: Geometrical, Kinematic, and Mechanical Aspects of the Body, with Special Reference to the Limbs* (WADC Technical Report 55-159), Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1955.