

The effects of ankle compliance and flexibility on ankle sprains

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ABSTRACT

WRIGHT, I. C., R. R. NEPTUNE, A. J. VAN DEN BOGERT, and B. M. NIGG. The effects of ankle compliance and flexibility on ankle sprains. *Med. Sci. Sports Exerc.*, Vol. 32, No. 3, pp. 260–265, 2000. **Purpose:** The goal of this study was to examine the influence of changes in subtalar joint flexibility and compliance on ankle sprain occurrence. **Methods:** Muscle model driven simulations of 10 subjects performing the landing phase of a side-shuffle movement were performed. The passive flexibility or compliance of the subtalar joint was varied, and each subject-specific simulation was exposed to a set of perturbed floor conditions. **Results:** Increases in flexibility and compliance both led to an increase in the occurrence of excessive supination, while changes in flexibility had a greater influence. Changes in flexibility or compliance caused only small changes in the occurrence of excessive supination torques. **Conclusion:** These results suggest that increased mechanical laxity does not directly cause an increase in sprain occurrence during side-shuffle movements. **Key Words:** SIMULATION, INJURY, JOINT LAXITY

Ankle sprains are a common injury in sports. It is estimated that between 13.9% and 17% of all sports injuries are ankle sprains (6,14). Ankle sprains are associated with increased susceptibility to subsequent sprains, or chronic ankle instability in between 20% and 50% of all sprain sufferers (5,21). To help prevent reinjury, the cause of this increased susceptibility to sprains should be determined. Many factors have been thought to contribute to chronic instability, including increased mechanical laxity of the ankle joint complex (10,13). This increased laxity can be caused by stretching or rupture of the ligaments and capsule that span the talocrural and subtalar joints. However, it has not been shown whether increased mechanical laxity of the ankle joint complex contributes to increased ankle sprain susceptibility or whether the mechanical laxity is a benign consequence of the ankle sprains.

Joint laxity may be associated with changes in either flexibility or compliance (11). Flexibility is defined as an angular displacement for a given torque. Compliance is defined as torque for a given angular displacement. However it has not been studied yet whether the flexibility or the compliance influence the susceptibility for injuries in a similar or different way from one another and whether one or the other is more important in this context.

Flexibility can be determined by exerting a known torque and measuring the corresponding angular displacement. Compliance can be determined by prescribing a known

angular displacement and measuring the corresponding torque. Flexibility or compliance are then calculated as the ratio of the torque and displacement. For linear elastic systems, doubling the flexibility is exactly the same as doubling the compliance. However, the ankle joint is not linearly elastic. Therefore, changes in flexibility are not the same as changes in compliance (Fig. 1). For example, because range of motion of a joint is the range of angular displacement through which it can be moved for a given (relatively small) torque value, range of motion is doubled when flexibility is doubled, but range of motion may increase only a small fraction when compliance is doubled. The mechanical laxity of a joint is often only assessed by examining its range of motion (18), and no distinction is made between flexibility and compliance.

If mechanical laxity after a previous injury increases sprain occurrences, then decreased flexibility or compliance of the joint may reduce the incidence of respraining. Ankle compliance and flexibility can be influenced by ankle taping and bracing (7,20), and the use of ankle braces has been shown to reduce the incidence of spraining (23) and respraining (22). Taping or bracing may reduce the incidence of spraining simply by bearing some of the torque applied to the ankle directly or by preventing the occurrence of large torques. However, it is not certain that these mechanical factors affect sprain occurrence because taping and bracing may affect sprain frequencies by other mechanisms, such as improving proprioception (8).

To determine whether altered mechanical compliance or flexibility of the ankle affect the occurrence of ankle sprains, a controlled study is required. The controlled manipulation of joint laxities without affecting other factors such as proprioception has not been achieved *in vivo*, and it

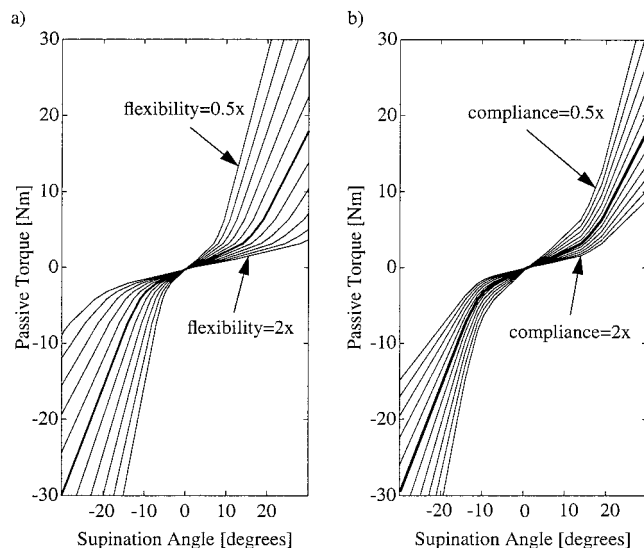


Figure 1—The angle-torque curves for the subtalar joint with varying flexibility (a) and varying compliance (b).

is not possible to study ankle sprains directly for ethical reasons. *In vitro* investigations are not sufficient because muscle forces are difficult to simulate and repeated tests to failure of the same specimen would not be possible. A forward dynamics simulation model has been developed that seems suitable for the investigation of ankle sprains (24) and permits the manipulation of the mechanical properties of the ankle.

Therefore, the purpose of this study was to determine the influence of mechanical flexibility and compliance of the subtalar joint on simulated ankle sprain susceptibility. This information may help to improve the understanding of the cause of chronic ankle instability and may aid in the design and the use of taping and bracing and the planning of surgical reconstructions.

METHODS

Forward dynamics simulation. The forward dynamics simulation model was developed using DADS (version 8.5, CADSI, Coralville, IA) and has been described in detail previously (24). The model consisted of rigid bodies representing the segments of the right leg of a 180-cm tall, 75-kg male (Fig. 2). The torso, head, arms, and the other leg were represented by a visceral mass and a rest-of-body segment. The subtalar joint and talocrural joint were represented by revolute joints aligned with joint axes based on Inman (9). Passive nonlinear joint stiffnesses were applied as moments about the subtalar and talocrural joint axes to represent the effects of passive soft tissue and bony constraints on movements about these axes (3). For the knee, the center of rotation of the shank relative to the thigh moved in the sagittal plane as a function of knee flexion angle. Adduction/abduction and internal/external rotation were permitted at the knee and were limited by passive moments. The hip joint was modeled as a spherical joint.

The model was actuated by 14 muscle groups, each representing one or several functionally similar muscles. These

muscle groups were the gluteus maximus, gluteus medius, adductor magnus, iliopsoas, rectus femoris, hamstrings, vasti, gastrocnemius, soleus, flexor digitorum, tibialis posterior, tibialis anterior, extensor digitorum, and peroneals. The flexor and extensor digitorum represented the function of the muscles of the digits as well as the hallucus. The peroneal muscle group represented the peroneus longus, brevis, and tertius. Each muscle had an origin and insertion fixed relative to the model segments, and several muscles had additional points through which the muscle passed to prescribe more anatomically accurate muscle paths (4). The muscle force-length-velocity-activation characteristics were modeled using a Hill-based model controlled by square-wave stimulation patterns. The stimulation onset was permitted to be before the simulation started so that the muscle activation could be increasing before touchdown.

The contact between the foot and the ground was represented by 66 discrete independent contact elements, each representing the mechanical properties of a region of a shoe sole and the underlying soft tissue (24). The 66 contact elements were distributed across the plantar aspect of the foot to represent the geometry of a flat running shoe, and the mechanical properties were selected to represent a running shoe of moderate hardness (24).

Ankle sprain simulations. Forward dynamics simulations of the first half of stance phase of a side-shuffle movement were performed. Initial kinematic conditions for the simulations were taken from the mean measured limb segment positions, orientations, and velocities at touchdown of 10 subjects performing a side shuffle movement (16). Muscle stimulation patterns were selected that minimized the difference between the measured and simulated movements for the flat surface condition for one subject as described before (24). These same muscle stimulation patterns were then used to perform simulations for 10 subject-specific sets of initial conditions on 50 irregular floor conditions, with 11 different values for the ankle compliance

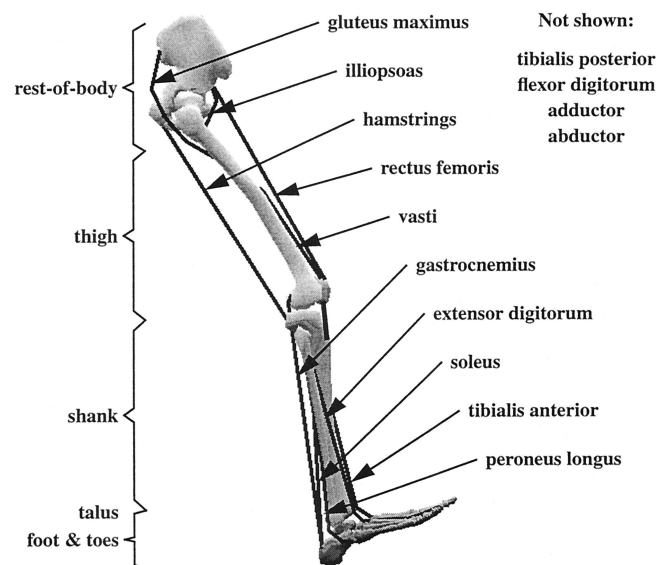


Figure 2—The body segments and muscles represented in the simulation model.

and then 11 different values of ankle flexibility (for a total of 11,000 simulations). For each simulation, maximum supination and maximum supination torque were recorded. The torque values recorded were those applied to the passive resistance at the subtalar joint and did not include the load on the muscles. In real subjects, these torques would be resisted by bony constraints and ligaments.

Exposure to an uneven surface was used as a model for ankle sprain injury. The floor in the computer simulation was divided into four quadrants, with the intersection of the four quadrants located at the middle of the shoe (at touchdown). The 50 irregular floor conditions were generated by varying the height of each quadrant with a uniform random distribution over ± 10 cm. The vertical position of the simulation model was adjusted so that the foot was just touching the highest point on the floor at the beginning of the simulation (touchdown). Thus, 500 simulations were performed for each experimental condition: 50 surfaces \times 10 subject-specific sets of initial conditions.

The passive mechanical properties of the subtalar joint were based on the torque-angle curves presented in Chen et al. (3). The flexibility was varied by scaling the angle values by 11 different factors ranging from 0.5 to 2. Then the compliance (1/stiffness) was varied by scaling the torque values by 11 different factors ranging from 0.5 to 2 (Fig. 1). The nonlinearity of the torque-angle curves meant that variations in compliance were not identical to variations in flexibility.

A sprain can be said to have occurred for any given simulation when the torque about the subtalar joint exceeds some given value, or when the angular displacement at the subtalar joint exceeds some given value. The absolute magnitude of the threshold at which an injury occurs would be difficult to determine and is likely to vary considerably between subjects. Therefore, a range of threshold values were used and the number of simulations that resulted in maximum torques or displacements greater than these threshold values were determined.

RESULTS

Increased flexibility of the subtalar joint caused an increase in the occurrence of excessive supination (Fig. 3). Regardless of the threshold angle selected, an increase in flexibility always caused an increase in the number of simulations that exceeded that threshold. The same is not true of the number of simulations that exceed a threshold supination torque. The change in frequency of excessive torques with changing flexibility depends upon the torque threshold selected. For moderate torque thresholds of between 20 and 40 Nm, the frequency of excessive torques increases with increasing flexibility.

Increased compliance also caused an increase in the occurrence of excessive angular displacements (Fig. 4). The influence of increased compliance on the occurrence of excessive supination torques also depended upon the threshold selected, but the influence was small. For both the occurrence of excessive torques and angular displacements,

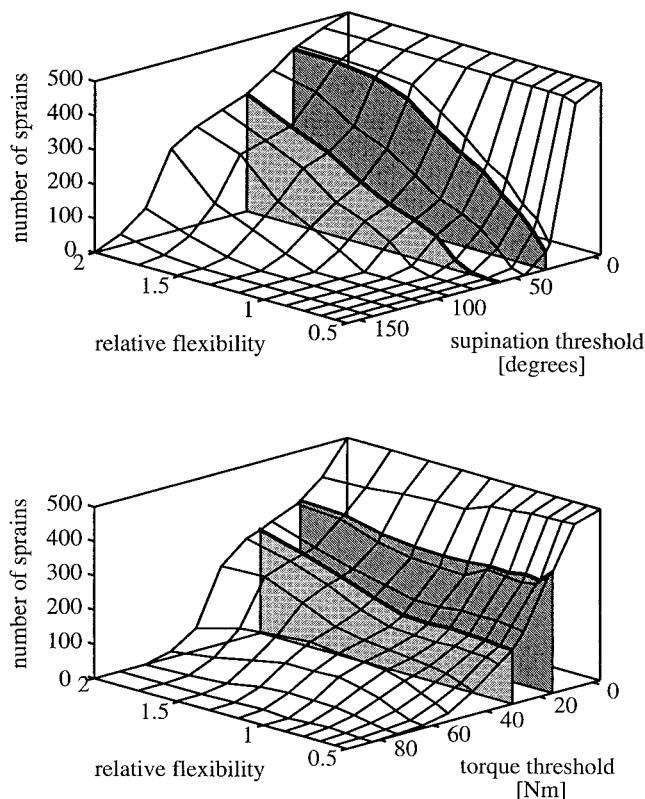


Figure 3—The number of sprains as a function of flexibility and supination threshold angle (top panel) or supination torque (bottom panel). Sprains are defined as occurrence of either supination angle (top panel) or passive supination torque (bottom panel) exceeding the threshold value. The dark and light shaded supination angle threshold values are 30° and 60°, respectively. The dark and light shaded supination torque threshold values are 15 and 30 Nm, respectively.

the influence of changes in compliance was smaller than the influence of changes in flexibility.

The influence of flexibility on sprain occurrence varied across subject-specific sets of initial conditions (Fig. 5). Also, the sensitivity to the threshold value varied across subjects. For some subjects and threshold values, the number of sprain occurrences increased sharply over only a small range of flexibility values, whereas for other subjects and threshold values, the variation in sprain occurrence was small.

Mean (across all 500 simulations) peak supination angle increased with increasing subtalar joint flexibility (Fig. 6). Mean peak supination angle also increased with increasing compliance but at a lower rate than with increasing flexibility. Mean peak supination torques increased with increasing subtalar joint flexibility, whereas mean peak supination torques stayed relatively constant with increasing ankle compliance.

DISCUSSION

The purpose of this study was to determine whether and how flexibility and compliance of the subtalar joint contribute to sprain susceptibility. In this study, torques and displacements about the subtalar joint were examined, but ankle sprains most often consist of injury at the talocrural

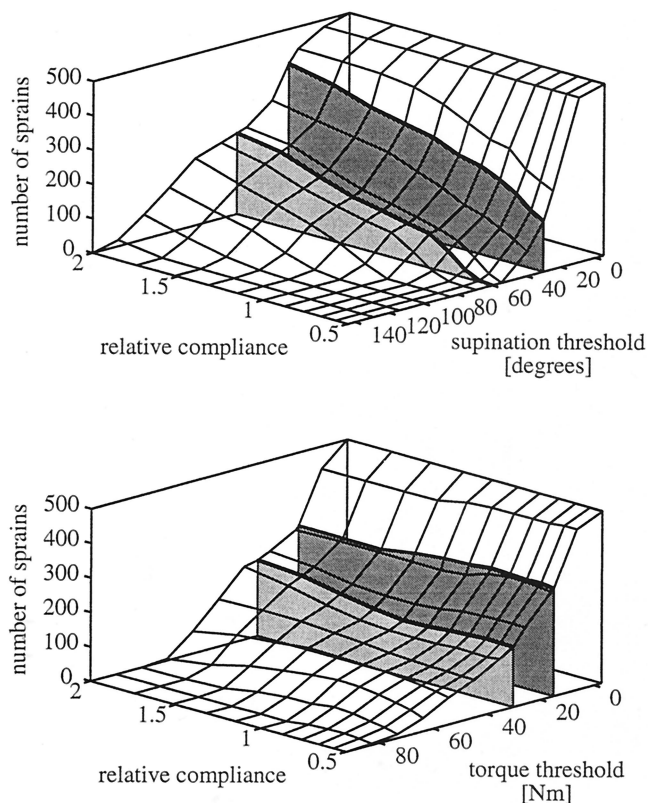


Figure 4—The number of sprains as a function of compliance and supination threshold angle (top panel) or supination torque (bottom panel). Sprains are defined as occurrence of either supination angle (top panel) or passive supination torque (bottom panel) exceeding the threshold value. The dark and light shaded supination angle threshold values are 30° and 60°, respectively. The dark and light shaded supination torque threshold values are 15 and 30 Nm, respectively.

joint. However, because no muscles are attached to the talus, no external loads are applied to the talus. In addition, the talus is small; torques applied to the passive structures at the talocrural joint must be transmitted through the talus from the subtalar joint. Therefore, large torques about the subtalar joint correspond to large torques at the talocrural joint about an axis parallel to the subtalar joint and consequently may lead to sprains if the load exceeds the strength of the ligaments.

For the simulations in this study, increases in flexibility or compliance had little influence on excessive torque occurrence. Because excessive torques were assumed to cause the damage to ligaments during an ankle sprain, these results suggest that an ankle that is simply more flexible after an ankle sprain will not have a considerable change in the occurrence of injury from normal, provided that the torque required to cause an injury (i.e., the strength of the ligament) has not changed. This lack of influence of ankle flexibility on sprain occurrence fits with the findings of McKnight and Armstrong (15), and Birmingham et al. (2), who found no differences in the range of motion of the ankle between normal and chronically unstable ankles.

Another possible mechanism of increased sprain susceptibility after ankle sprain is a decrease in strength of the ligaments. It is possible, particularly shortly after an initial injury, that an ankle sprain causes a decrease in strength of

the lateral ligaments of the ankle because of incomplete healing of a tear. That is, there may be changes not in the compliance or flexibility of the ankle, but in the absolute strength of the ankle. In this current study, this would correspond to a decrease in the torque threshold above which a sprain occurs. In the current study, it was found that the number of sprains increased considerably as the torque threshold decreased, and therefore, if there is a decrease in the strength of the lateral ligaments, this would cause an increase in the occurrence of sprains. However, there is no evidence of decreased strength of the ligaments without a change in ankle flexibility or compliance in chronically unstable ankles reported in the literature (17).

When ankle braces or tape are used to help prevent sprains, the excessive torque may be borne partially by the brace or tape, and damage to the ligaments will only occur if the ankle is inverted excessively. Therefore, occurrence of excessive supination is the measure that should be used to evaluate injury risk in the taped or braced ankle. For this simulation model, both increased flexibility and increased compliance caused increases in the occurrence of excessive supination. Because the ankle tape or ankle brace can support the excessive load (7), it may be by this simple mechanism that taping and bracing prevent reinjury of ligaments, rather than by reducing the probability of excessive torques through improved proprioception. However, the torque that tape and bracing can support is much smaller than that which the muscles crossing the ankle can support (1), so it remains unclear whether this can account for the observed decrease in sprain occurrence with ankle tape or braces.

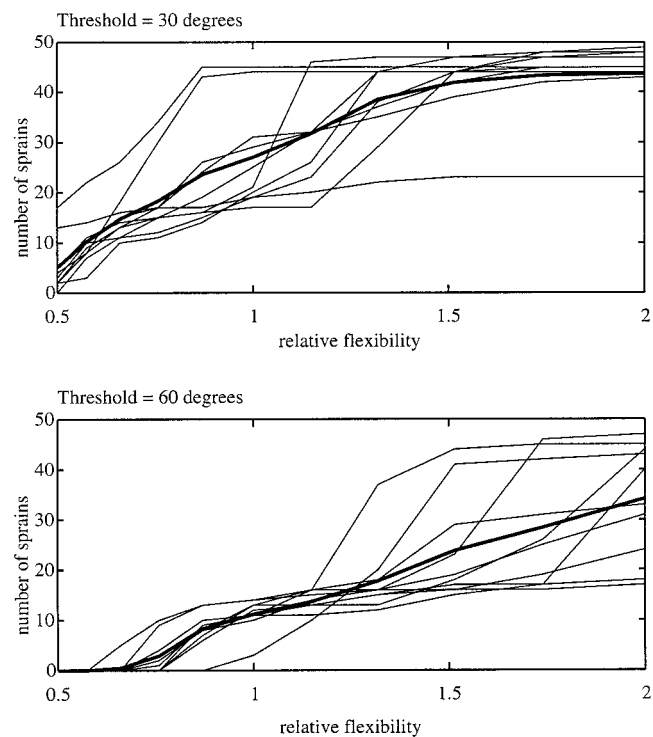


Figure 5—The number of sprains as a function of flexibility and supination threshold angle for each set of initial conditions (*thin lines*) and the mean across all sets of initial condition (*thick line*). The supination angle threshold values are 30° and 60° for the top and bottom plots, respectively.

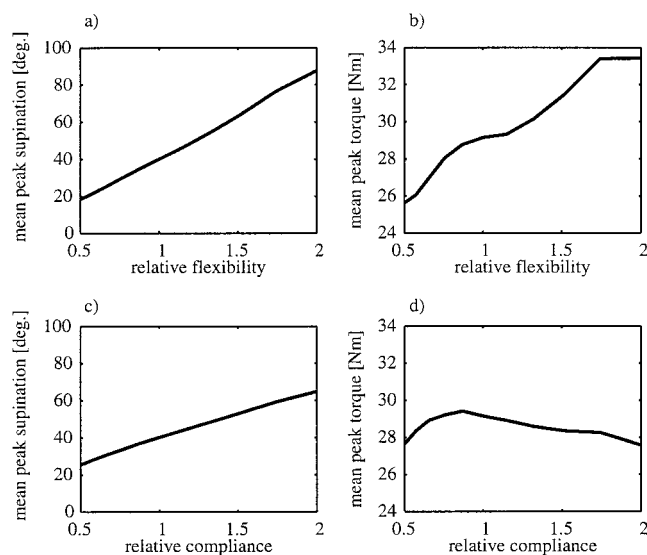


Figure 6—Mean (across 500 simulations) peak supination angles vs flexibility (a), mean peak supination torques vs flexibility (b), mean peak supination angles vs compliance (c), and mean peak supination torques vs compliance (d).

Changes in flexibility had a greater influence than changes in compliance on the occurrence of excessive torques and displacements. The difference between changes in compliance and flexibility is small for small angular displacements of the subtalar joint. However, at large angular displacements of the joint, the torque-displacement curve is nonlinear and the difference between flexibility and compliance is more evident. A joint that is more flexible (rather than more compliant) has an increased range of motion. This potentially increases the lever arm of external forces relative to the subtalar joint axis, hence the larger effect influence of flexibility on occurrence of sprains. Ankle taping and braces reduce both flexibility and compliance, with different braces influencing flexibility and compliance to differing degrees (7,19). Ankle taping has been shown to reduce the range of motion of the ankle during walking (12), presumably by changing the flexibility or compliance of the joint at joint angles far from the ends of the range of motion of the joint. Because a decrease in flexibility caused a greater decrease in the occurrence of excessive supination than a decrease in compliance in the current study, an ankle brace or tape application should be designed to limit the range of motion in supination, rather than simply stiffening the ankle, if injury prevention is the goal. Such a restriction on joint movement may negatively

influence sports performance, which must be taken into consideration.

Changes in ankle flexibility or compliance may contribute to injuries other than inversion sprains and may influence the severity of sprains. It is expected that landing on the irregular floors as used in this study would have caused significant changes in the movement and loads in locations other than the ankle, and these movements may have resulted in injuries. Specifically, increased stiffness at the subtalar joint may have increased ligament loading at the knee when landing on uneven surfaces. However, no attempt was made to examine this in the current study.

The simulation model showed varying results for different initial conditions, indicating that the touchdown kinematics of the movement influenced the susceptibility to sprains. Therefore, if movements other than side-shuffle were examined the results of the study may have varied. Also, because different touchdown conditions influenced the results, changes in flexibility or compliance may have an indirect influence on sprain occurrence. For example, changes in flexibility or compliance of the ankle may influence the ability of the neuromuscular system to position the ankle, thereby indirectly influencing sprain occurrence in a way that is not accounted for in the current study. Furthermore, because several factors associated with a history of ankle sprains such as impaired proprioception, coordination, or muscle strength may lead to perturbations in the touchdown joint position, these other factors may have a greater influence on sprain occurrence than flexibility or compliance. However, examining the influence of flexibility and compliance independent of these other factors was the objective of this current study and is required before these other factors can be examined and understood.

In conclusion, if injuries are associated with excessive torques (as in the unprotected ankle), then neither flexibility nor compliance have much influence, but if injuries are associated with excessive supinations (as they are with braced or taped ankle) then decreased occurrences of injuries may be achieved by reducing ankle flexibility.

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