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The Effect of Ankle Braces on the Prevention of Dynamic Forced Ankle Inversion*

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Background: Athletes often employ prophylactic braces to reduce the risk of ankle injuries.
Hypothesis: Ankle braces do not significantly decrease the risk of forced inversion on a standardized one-footed jump landing.
Study Design: Controlled laboratory study.
Methods: Fourteen healthy men with a mean age of 25.1 years were tested. Three braces, two semirigid (Aircast and Bledsoe) and one lace-up (Swede-O), were fitted to each subject. Forced dynamic ankle inversion of 24° was to be resisted as the subjects landed on one foot with a force of two body weights on a stimulus presented randomly in 5 of 15 jump trial blocks onto a hard, level force plate. Subjects first completed 1 no-brace block of 5 trials to establish baseline performance, then 3 randomly ordered 15-trial blocks testing performance with each of the braces, and then finally a no-brace 5-trial block.
Results: The average no-brace success rate was 24%, which demonstrated the challenging nature of the task. All three braces increased the success rate (average, 44%); however, only the two semirigid braces proved to be significantly better than the unbraced state.
Conclusion: This test holds promise for evaluating brace efficacy when landing with one foot unexpectedly on an object that acts to forcibly invert the ankle.

More than two million people are affected by ankle injuries in the United States each year.[17] Athletes often employ prophylactic braces to reduce the risk of ankle injuries. The effectiveness of such devices has been reviewed elsewhere.[2] Their efficacy has been assessed by using both quasistatic in vitro tests[13] and in vivo tests,[4–7,14] but the rate of application and the magnitude of the ankle inversion moment failed to approach those that must be acting on the lower extremity when a subject lands from a jump. The other form of brace testing is field testing. However, whether the studies were retrospective[12] or prospective,[16,19,21] the inversion moments acting in field testing were unknown. A more realistic, dynamic, and standardized test of lower extremity loading is needed to evaluate new braces before field testing.

A challenging dynamic test was developed to study the ability of the musculoskeletal system to prevent ankle inversion under the one-footed jump landing condition (M. Milia et al., unpublished data, 1998). The results from that test showed that healthy subjects could significantly increase their rate of success in resisting unwanted inversion if they had advance knowledge of the presence of the provocation causing inversion. To ensure subject safety the test was designed so that ankle inversion could not exceed the given angle limit, thereby protecting the ankle joint from injury. In the present study we employed this same test to examine the efficacy of three braces in resisting ankle inversion.

We tested the null hypothesis that, compared with the average of the nonbraced trials, all three ankle braces would not increase the subject's success rate in resisting a standardized dynamic forced-inversion stimulus. The stimulus, if unresisted, resulted in 24° of foot inversion within 40 msec when the subject landed on one foot from

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a jump with a peak ground impact force equivalent to two body weights.

MATERIALS AND METHODS

Subjects

Fourteen healthy male subjects who ranged in age from 21 to 36 years (mean, 25.1 ± 3.6) agreed to participate and gave their written informed consent according to Institutional Review Board guidelines. Their shoe size ranged from 10 to 11.5. None had a history of ankle injury within the past 6 months. Their habitual physical activity level, assessed on a scale from 0 to 10,[23] had a mean value of 5.4 ± 3.3 units.

Protocol

In an attempt to induce dynamic inversion of the ankle, a special detachable sole was fabricated similar to that developed in our previous study (M. Milia et al., unpublished data, 1998). This sole, made of Aquaplast (WFR/Aquaplast Corp., Wyckoff, New Jersey) and heat-molded to fit a Nike low-top basketball shoe (Nike, Inc., Beaverton, Oregon), included a 6-mm wide fulcrum placed 20 mm medial to the midline, running the length of the shoe. The fulcrum was 27 mm high and caused a maximum shoe sole inversion of 24° when the outer edge of the shoe sole touched down to a hard, level support surface. This design was chosen to ensure a provocation that would result in a foot inversion stimulus of realistic rapidity and magnitude that would be familiar yet pose minimal risk of injuring the ankle ligaments. Injury to ankle ligaments occurs when inversion at the subtalar joint exceeds 30° of inversion.[1] The provocation mimicked landing with more than full body weight on a hard object (for example, an opponent's foot or a rock) interposed between the medial aspect of the shoe sole and an unyielding surface.

We tested three braces: Swede-O Ankle Lok (Swede-O-Universal, Inc., North Branch, Minnesota), Aircast Sport-Stirrup (Aircast, Inc., Summit, New Jersey), and the Bledsoe Ultimate Ankle Brace (Bledsoe Brace Systems, Grand Prairie, Texas) (Fig. 1). The Swede-O Ankle Lok is constructed of nylon with an elastic back and has a lace-up design (Fig. 1A). The Aircast Sport-Stirrup is a semirigid brace that conforms to both the medial and lateral sides of the ankle via air-filled padding between the skin and the rigid plastic composite (Fig. 1B). The Bledsoe Ultimate Ankle Brace is also described by the manufacturer as a semirigid design with metal stays (Fig. 1C) anchoring it to the shoe beneath the inner sole, permitting the shoe to control the foot. It is adjustable for both width and position within the shoe. A metal hinge located at the lateral and medial malleoli permits both dorsiflexion and plantar flexion.

During trials in which no brace was worn, an individually customized heel cup (made of Aquaplast) was worn to reduce relative motion between the shoe and heel. Minor modifications were made to the low-top shoe: VELCRO

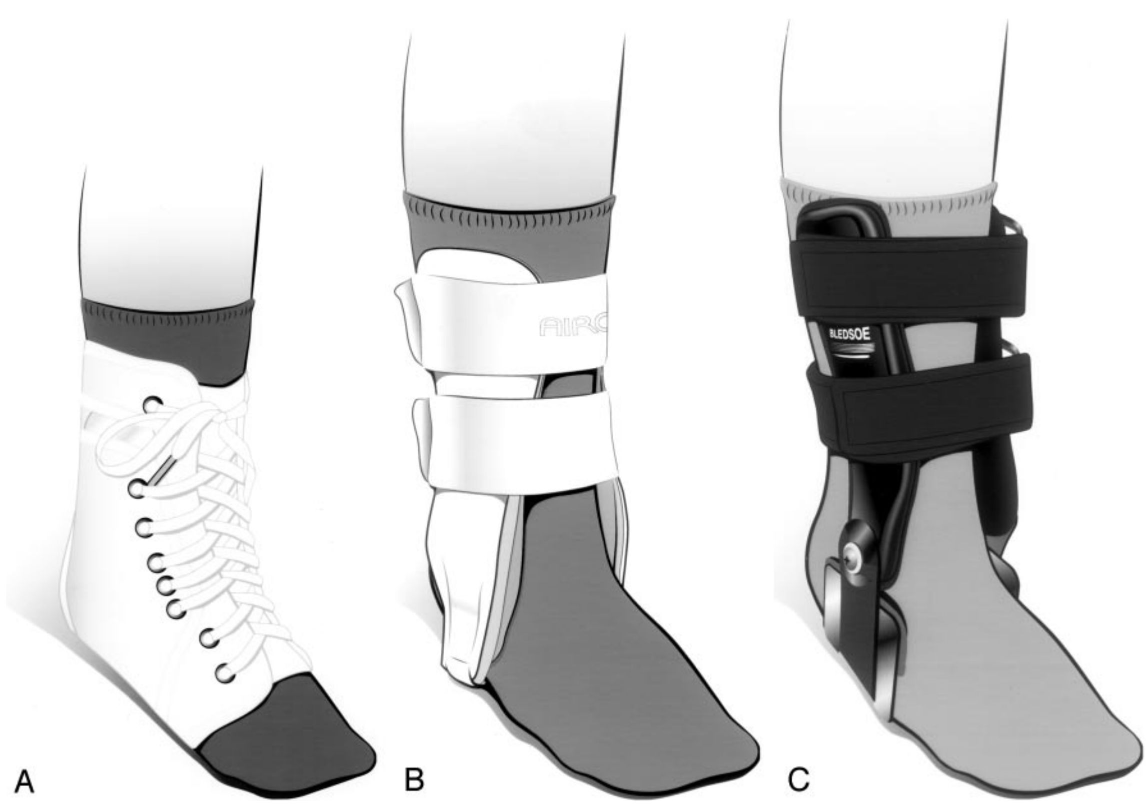

Figure 1. The braces used in this study: A, Swede-O; B, Aircast; and C, Bledsoe.

(VELCRO USA, Manchester, New Hampshire) was affixed to the bottom of the Swede-O, the Aircast, and the inside of the heel cup to reduce relative motion between the brace and the shoe. VELCRO was also attached to the insole to reduce relative motion of the insole relative to the shoe. The Bledsoe is designed to adhere to the upper surface of the shoe sole proper with VELCRO. No modifications were made to its design.

During testing, a microcomputer was used to gather data at 1.8 kHz from a six-channel AMTI force plate (Model OR-6, AMTI, Inc., Newton, Massachusetts). The signals were amplified to volt levels and sampled by using a 12-bit analog-to-digital converter. One channel of the converter also monitored the state of a switch circuit that monitored touchdown of the lateral margin of the foot, if it occurred. If such contact occurred during the time interval of 1.5 seconds after touchdown (as monitored by the force plate), the trial was scored a failure; if such contact did not occur within 1.5 seconds of touchdown, the trial was scored a success. The switch circuit consisted of a 1-cm wide aluminum foil strip adhered under the lateral margin of the shoe sole along its length and a 10-cm wide strip of aluminum foil adhered to the force plate under the landing zone. Contact of the two strips with a few grams of force completed a 9-volt DC circuit, and that event was recorded by the microcomputer via the analog-to-digital converter.

The subject jumped from a take-off platform a total forward distance of 60 cm onto the center of a force plate. The take-off platform was designed with a sagittally aligned groove that was 30 mm deep and 5 cm wide and received the fulcrum so that its physical presence was concealed from the subject (Fig. 2). He could neither feel nor see it as he bore weight on that foot before and during the take-off phase of the jump. Subjects were instructed to jump so that they landed with a force of twice their body weight on their right foot and then to try to balance for at least 3 seconds. Allowable variability in the peak ground reaction force for that data to be acceptable was 10%; namely, from 2.0 to 2.2 times body weight, as displayed in real time on a 50-MHz storage oscilloscope. Each subject was first allowed to practice jumping without either sole (flat dummy sole or the sole with the 20-mm fulcrum attached) so that he could consistently land such a jump within the required ground reaction force limits. Subjects were then told that the fulcrum would be present only in some trials and that they should try to prevent the outside of their foot from touching down on the platform when it was present. Either the fulcrum sole or a flat dummy sole was attached to the shoe while the subject sat in a chair just behind the take-off platform with his eyes closed. The right foot was then placed on the platform so that the fulcrum, if present, entered its receiving groove and was held in place while the subject was asked to stand up. After opening their eyes, the subjects jumped onto the center of the force plate and balanced on their right foot. Touchdown of the lateral margin of the shoe sole, if it occurred, was detected when the aluminum tape lining the outside of the Aquaplast sole completed the electrical detection circuit.

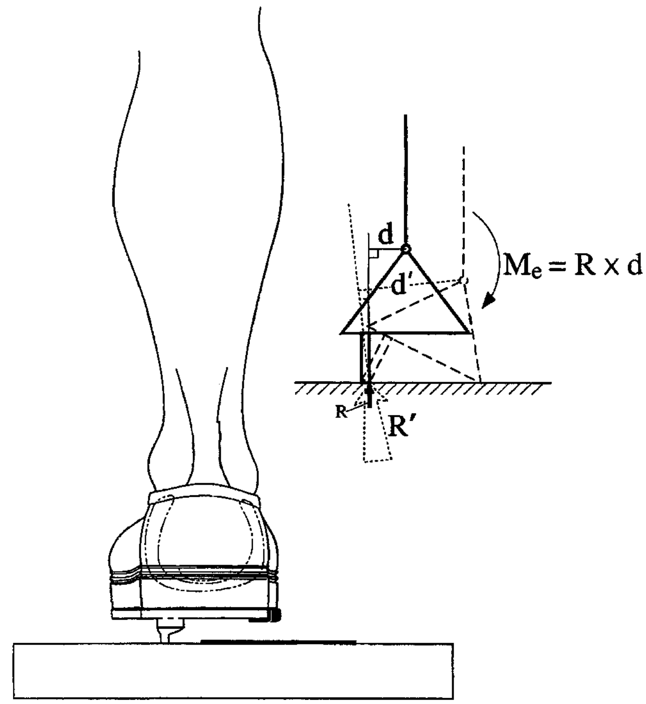

Figure 2. Posterior view of the unbraced right foot in the low-top shoe at the instant of touchdown onto the instrumented force plate. The placement of the fulcrum can be seen as well as the aluminum strip under the lateral margin of the sole (thick lines) that contacted a similar strip on the force plate (thick line) to signal that the subject has failed to prevent 24° of inversion after touchdown. The inset shows the initial ground reaction force (R, solid arrow) acting through the fulcrum with a lever arm, d, about the subtalar joint when the fulcrum first contacted the floor at touchdown. As the value of R increased to its peak value, R′, it acted with a lever arm, d′, about the subtalar joint, causing the external moment, M_e, which acted to rapidly and forcibly invert the shoe and subtalar joint into the dashed configuration. If unresisted by the brace and peroneal muscles, inversion failure typically occurred within 40 msec, before the ground reaction force had reached one-third of its peak value.

The first trial block of 15 jumps (5 forced inversions randomly inserted into the presentation of 10 dummy trials) was conducted without a brace to establish baseline performance in the low-top shoe. The next three blocks were conducted with each of the three braces, and the last block was again conducted without a brace to check for the presence of a practice (learning) effect. The ordering of the brace trial blocks was randomized.

At the conclusion of the final trial, subjects were asked to rank the braces based on their comfort and confidence in the brace. They were also asked to discuss other reasons why they would or would not wear the different braces.

The outcome variable was expressed as the number of successful trials of a possible total of five trials per trial block for each subject. The resulting success rate (SR) was defined as a ratio, the value of which could only range from 0 to 1. Logistic regression analysis of the form SR = exp (b0 + b1*x)/(1 + exp [b0 + b1*x]) (where SR is the proportion at each value of the variable X, b0, and b1 are numerical constants to be estimated, and exp is the exponential function) was then used to compare any two test conditions with a standard statistical analysis package, SAS v. 6.1.2 (PROC GENMOD, SAS Institute, Cary, North Carolina), to estimate the regression constants b0 and b1 by least-squares and test each hypothesis by using the value of b1. Braced trial results were compared with the averaged results from the first and fifth (no-brace) trial blocks. A P value of less than 0.05, indicating that b1 was significantly greater than zero, was considered statistically significant.

RESULTS

Unbraced Performance

The results show that this was indeed a challenging test (Table 1). In the unbraced state represented by the first trial block, these healthy subjects succeeded in preventing the foot from rotating through the full 24° of inversion an average of 0.9 trials of five trial attempts, equivalent to an 18% success rate. Half of the subjects (7 of 14) were completely unsuccessful in all five trials.

Practice Effect

Although there was an increase in the success rate in the unbraced state from the first trial block to the fifth trial block, from 0.9 (which was equivalent to an 18% success rate) to 1.5 (30% success rate), this difference did not reach statistical significance (P = 0.062). The average unbraced condition was 24%. Although one subject admitted consciously attempting to devise strategies to improve success at preventing inversion, a more common description was merely a perception of having "learned to perform the test better" as the trials progressed. Only three of the seven subjects (Nos. 3, 6, and 13) who were completely unsuccessful in the first trial block achieved any measure of success in the fifth trial block, and one subject (No. 2) who was partially successful in the first trial block was completely unsuccessful in the fifth trial block.

Brace Effect

The primary hypothesis was rejected, in that all three braces increased the subjects' success rates in resisting the ankle inversion stimulus with respect to the averaged performance in blocks one and five (Table 1). For example, when compared with the averaged unbraced success rate (24%), the Bledsoe (52% success rate; P = 0.006) and Aircast (46% success rate; P = 0.006) braces were most effective in preventing inversion. Although the Swede-O brace also prevented ankle inversion (34% success rate), the difference compared with the unbraced state was not statistically significant (P = 0.12). There were no significant differences between the Bledsoe and Aircast braces (P = 0.56), or Aircast and Swede-O braces (P = 0.14). However, the Bledsoe performed significantly better than the Swede-O (P = 0.047). The best brace performance yielded an average success rate of 52%, or nearly three times that of the initial unbraced performance (18%). Even allowing for a practice effect, this success rate was equivalent to twice that achieved in the unbraced state, thereby highlighting the prophylactic potential of these devices in this challenging test.

Subjective Evaluation

After the testing, each participant was asked to rank the three braces according to 1) confidence in protecting the ankle from a potential injurious situation and 2) overall comfort. Interestingly, subjective ratings of the braces differed greatly between these two categories. In terms of

TABLE 1
Mean, Standard Deviation (SD), and Number of Successful Trials in Preventing 24° Inversion of the Five Attempts in Each Trial Condition

Subject	No-brace no. 1	Swede-0	Aircast	Bledsoe	No-brace no. 2
1	0	0	0	3	0
2	1	4	3	2	0
3	0	3	2	2	2
4	2	0	1	0	2
5	3	2	5	2	2
6	0	1	1	4	1
7	1	2	5	3	3
8	0	0	0	0	0
9	2	4	3	5	2
10	2	1	3	3	3
11	0	0	0	0	0
12	0	3	4	4	0
13	0	1	2	3	4
14	1	3	3	5	2
Mean (SD) success score	0.9 (1.0)	1.7 (1.5)	2.3 (1.7)	2.6 (1.7)	1.5 (1.3)
Average success rate	18%	34%	46%	52%	30%

confidence in ankle stability, 8 of 14 subjects ranked the Bledsoe brace first, whereas the Aircast received 5 of 14 first-place votes. However, a trade-off appeared between confidence and comfort. Even though 9 of 14 subjects ranked the Swede-O brace third in terms of brace stability, 10 of 14 subjects thought that the Swede-O brace was the most comfortable, suggesting that subjects were more comfortable in the Swede-O but more confident in the Aircast and Bledsoe. Also noteworthy is that two subjects who regularly played soccer found that the Bledsoe brace would not allow sufficient motion of the foot for them to play soccer normally.

DISCUSSION

The primary goal of this study was to test three modern ankle braces in a challenging dynamic provocation test to determine how much protection these braces offered from forced inversion during a jump landing. The results showed that all three braces increased the likelihood of preventing inversion in a jump landing; two braces proved significant in this regard.

Ankle braces can help prevent ankle inversion by increasing the rotational stiffness of the ankle joint to forced inversion. In our test situation, the external rotation moment acting to invert the ankle was caused by a medially placed vertical peak ground reaction force of approximately two body weights. This loading was realistic in that it mirrored the situation of inadvertently landing from a jump on an opponent's foot or on some other rigid foreign body, like a stone, located unexpectedly under the medial aspect of the foot. Such an inversion rotation moment must be resisted by a combination of the neuromuscular system activity, comprised chiefly of increased peroneal muscle stiffness,[1] and the rotational stiffness of the brace about the subtalar joint axis. The rotation moment must therefore be resisted by the musculoskeletal stiffness and brace in proportion to their relative stiffness. In other words, the stiffer the brace and its interface with the foot, the greater the proportion of the external rotation moment the brace will resist and the less the peroneal muscles and lateral ligamentous tissues have to resist. The Bledsoe and Aircast must therefore have a higher rotational (inversion) stiffness than the Swede-O brace.

Ankle braces can also help prevent forced inversion by positioning the ankle joint in a neutral posture, thereby preventing the more common inverted posture that exists after a jump and before landing with an unbraced ankle. For example, Milia et al. (unpublished data, 1998) have shown, by using skin markers on the rearfoot and tibia, that the more inverted an ankle is at touchdown, the greater the likelihood that an excessive angle of inversion may be reached during the landing. Braces help eliminate inversion of the talus and calcaneus before impact.[20] Under less challenging circumstances, like landing on irregular compliant surfaces, this may help delay peak inversion long enough to allow reflexive evertor muscle recruitment to augment resistance to inversion.

Repeated testing of the same subject raises the possibility for practice effects to affect outcome. However, trial block randomization helped to minimize systematic bias due to practice and fatigue effects. Using verbal feedback and knowledge of results, subjects quickly learned in the practice trials to jump high enough to reliably land with two body weight magnitude ground reaction forces. They also displayed a trend toward learning to improve their success rate between blocks 1 and 5, although the trend did not achieve statistical significance. The mechanism by which they achieved slightly greater success in block 5 is unclear. The possibilities are that subjects might have learned to land with less foot inversion or to proactively recruit their evertor muscles more fully before touchdown, or both, thereby developing greater resistance to inversion by the time inversion loading peaked (M. Milia et al., unpublished data, 1998). The more athletic subjects were more likely to improve over time; a slight association was identified between activity level and learning effect ($r^2 = 0.37$; $P = 0.19$). However, the presence of a practice trend does not negate the results because the order of presentation of the braces was randomized and could not favor any one brace. Leg muscle fatigue, which could have counteracted the practice effect on outcome, was minimized because subjects rested on a chair between every trial. During this rest period, one of the two shoe soles was chosen and mounted for the next trial without the subject being able to see or feel which one. Subjects were also allowed 5-minute rests between trial blocks to minimize evertor muscle fatigue.

In athletic activities, jump landings characteristically involve large ground reaction forces, often ranging from two to four times body weight, depending on the shoe surface compliance and height of the jump. However, the ground reaction forces can reach 3 to 14 times body weight, for example, in basketball rebounding, landing from a block in volleyball, and back somersaults in gymnastics.[3,8–11,15,18,22] The existence of such rapidly rising and large impact forces was the rationale for designing the dynamic brace tests that we used. We sought to reproduce more realistic testing conditions than have hitherto been used. The test that we used can easily be modified to include larger peak ground reaction forces by simply instructing test subjects to land on the force plate from a higher jump. However, we deem it advisable to decrease the height of the fulcrum to limit the maximum angle of foot inversion to 18°[1] to eliminate all risk of injury to the lateral ankle structures. It is the height of the fulcrum relative to foot width that limits the maximum angle of shoe inversion that can be achieved.

A limitation of the outcome measure that we used was that it represented subjects' success rates in preventing the shoe *sole* from rotating 24° from the horizontal. At failure (lateral sole-floor contact), the os calcis may have inverted through this angle relative to the tibia, but it likely rotated through a lesser angle. The vertical ground reaction force, acting on the shoe through the fulcrum, would tend to cause the shoe sole to rotate relative to the os calcis because relative motion between the bone and shoe is impossible to eliminate. We attempted to minimize this relative motion by using a fitted molded heel cup. A better measure of inversion would have been to implant tantalum markers into the os calcis and tibia and to use cineradiography to measure the true inversion angle, but such a procedure was impractical. The next-best measurement strategy would have been to place pairs of skin surface markers on the skin over the os calcis and tibia and to measure the change in the included angle (M. Milia et al., unpublished data, 1998). In our earlier study, in which we used this technique, we found that the peak mismatch between inversion angle, measured with tibial and os calcis skin markers, and shoe angulation averaged less than 5°. Hence, this is our best estimate of the error in our angle measurement method.

CONCLUSIONS

All three braces tested (Aircast, Bledsoe, and Swede-O) decreased the probability of forced inversion at touchdown from a jump landing by nearly threefold. The Bledsoe and Aircast braces were more effective than the Swede-O in preventing inversion.

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