M. Estes
Research Assistant,
Department of Mechanical and
Aeronautical Engineering,
University of California,
Davis, CA 95616

E. Wang
Assistant Professor,
Department of Mechanical Engineering,
University of Nevada,
Reno, NV 89557

M. L. Hull
Professor of Mechanical Engineering and
Chair of Biomedical Engineering,
Department of Mechanical and
Aeronautical Engineering,
University of California,
Davis, CA 95616

Analysis of Ankle Deflection During a Forward Fall in Snowboarding

Toward the general goal of preventing ankle injuries in snowboarding accidents, the objective of this project to develop a dynamic system model of a snowboarder and assess which model parameters, particularly those attributed to the boot, most strongly influenced ankle deflections during a forward fall. To satisfy this objective, a system model was created that included the rider, the boots, the snowboard, and the snow as components. Through dynamic simulations, peak ankle deflections were computed over realistic ranges of input parameter values for each of the model components. Defining sensitivity as the total change in peak ankle deflection over the range of a particular parameter studied, results indicated that the peak ankle deflection was most sensitive to the boot stiffness. Although lower, the sensitivity of the peak ankle deflection to the snow model parameters was still significant, being roughly half of the boot sensitivity. Increases in both snow stiffness and snow damping caused higher ankle deflections. Variations in both snowboard stiffness and anthropometric parameters had little effect. Due to the strong dependence of ankle deflection on boot stiffness, the potential exists for mitigating the ankle injury problem through judicious design of the boot.

Introduction

The popularity of snowboarding has grown dramatically in recent years (Pino and Colville, 1989; Aitkens, 1990; White, 1995). The growth of the sport has been accompanied by increased injuries. The injury rate for snowboarding is on par with that of Alpine skiing (Ganong et al., 1992) but the nature of the snowboarder's injuries is unique. Injuries of the upper and lower extremities occur with similar frequency and the lower extremity is dominated by ankle injuries (Bladin et al., 1993; Ganong et al., 1992; Abu-Laban, 1991; Pino and Colville, 1989). The majority of lower limb injuries occur to the forward leg (Bladin et al., 1993; Pino and Colville, 1989). The rider's sideways stance puts the forward leg in a vulnerable position in the event of a fall. An important relationship between boot type and ankle injury is evident; ankle injuries occur mostly in riders who use soft boots (Bladin et al., 1993).

The construction of the two popular types of snowboard boots may reveal the reason for this relationship. Snowboard boots are categorized as either soft or hard, but soft boots are the more commonly used because hard boots (similar to Alpine ski boots) limit the snowboarder's ability to contort during maneuvers, especially aerials. Although the nature of snowboarding demands a flexible boot, evidence suggests that riders utilizing some sort of boot reinforcement experience less frequent and less severe injuries (Bladin et al., 1993). Accordingly, the optimum snowboard boot design would satisfy the rider's desire for flexibility and only incorporate the minimum necessary stiffness to mitigate ankle injuries.

Although advances in equipment design inspired by research have reduced the frequency of many common injuries in Alpine skiing (Robinson, 1991; Schaff and Hauser, 1993), little research has been aimed at mitigating snowboard injuries. Accordingly, the objective of this study was to use a dynamic model of a snowboarder to investigate the relationship between the maximum ankle deflection during a forward fall and model parameters, particularly those attributed to the boot. Because this is the first modeling study of snowboarding known to the authors, this objective is important both to directing future modeling efforts and to designing boots that limit ankle deflection through adjustment of boot parameters such as stiffness.

Contributed by the Bioengineering Division for publication in the JOURNAL OF BIOMECHANICAL ENGINEERING. Manuscript received by the Bioengineering Division January 31, 1996; revised manuscript received November 9, 1998. Associate Technical Editor: A. G. Erdman.

Methods

Model. The model was meant to represent a snowboarder (male of average height and weight) who has taken a jump and falls forward due to incorrect balance, landing with the board nose first (Fig. 1). A forward fall after an overrotated or unbalanced jump was a likely scenario to induce the hyperrotations necessary to cause ankle sprains, the most common lower limb injury among snowboarders as mentioned previously. The rider was assumed to be fully upright during flight and facing perpendicular to the plane of Fig. 1. The fall motion was restricted to occur in the plane of Fig. 1, which was defined as the "falling" plane.

The parallelogram linkage model of the rider consisted of the board, the two legs, and the pelvis as the links. The trunk, arms, and head were grouped together and modeled as an additional link fixed rigidly to the pelvis. The knee joints were assumed locked because the fall motion was assumed to occur in the "falling" plane. The reference values for the anthropometric parameters of the snowboarder were based on published anthropometric formulas derived from cadaver study data (Winter, 1990) (Table 1).

The ankles were modeled as torsion springs in parallel, representing the restoring action of the boots and ankle tissues. Ankle motion was defined about orthogonal axes as suggested by Chen et al. (1988) as shown in Fig. 2. The passive ankle flexion and inversion/eversion stiffness data were also obtained from Chen et al. (1988) and curve fit with cubic equations.

No models for snowboard boot stiffness were available so two arbitrary models were chosen. The restoring torques of the boots in inversion/eversion were modeled as either linear or quadratic functions of the ankle deflection. Since no snowboard boot data were available, the reference value of 500 Nm/rad was half of the maximum flexion stiffness values from Bally et al. (1989) for Alpine ski boots.

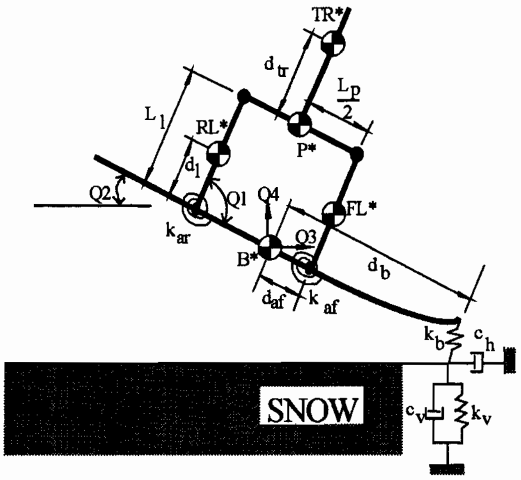

Fig. 1 Complete model of snowboarder with the generalized coordinates and input parameters indicated. Mass and moment of inertia parameters have been omitted for clarity.

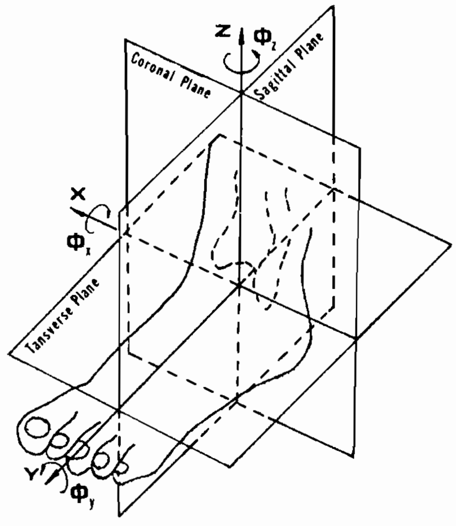

Fig. 2 Schematic view of the tibial reference frame and the definition of the rotations about its axes (from Chen et al., 1988)

The placement and orientation of the snowboarder's feet on the board was an unique aspect of the snowboarder model. By convention, foot orientation is measured about an axis perpendicular to the board with 0 deg defined as perpendicular to the snowboard's long axis. The forward and rear foot angles were set at 30 deg and 0 deg, respectively, which are the most common angles. Because neither of the forward foot's axes (as defined in Fig. 2) resided in the "falling" plane, the torque vector about the axis perpendicular to the "falling" plane was computed through a matrix transformation.

The snowboard was modeled as a linear spring that represented the stiffness perpendicular to the chord connecting the tip of the snowboard (undeflected position) to the center of the front foot. The reference stiffness value was measured from a commercially available board to be 1450 N/m.

The reaction of the snow was modeled separately in the vertical and horizontal directions. A spring and damper in parallel was used in the vertical direction. Both linear and quadratic functions were used to represent the snow deflection but the damper was modeled as linear. The quadratic function did not include the linear term. Mellor (1977) modeled snow as a linear spring and published a stiffness value of 10,000 N/m, which was used as the reference value. Following the recommendation made by Webster and Brown (1996), the reference snow damping value was set at 1000 Ns/m.

The reaction force in the horizontal direction was assumed to be strictly dissipative. This was based on the observation that snow has negligible energy storage capabilities horizontally. A linear damper modeled this behavior (Fig. 1).

Simulations. The simulations began with the rider in midflight. He was fully upright on a nose-down board, which was 45 deg from horizontal. The initial velocity of the rider/board was 8.94 m/s along the direction of the board. The nose of the board was chosen arbitrarily to be 1 m above the snow. The snowboard was assumed to have zero angular velocity. This initial configuration was based on an arbitrary scenario meant to represent a typical snowboard crash. At impact, the rider was in the same orientation as at the simulation start and landed on level ground. Impact with level ground was chosen as the worst-case scenario because any down slope during landing would tend to mitigate collision forces.

Pro/MECHANICA: *Motion,* a mechanism analysis software package (Parametric Technology Corporation, Waltham, MA), was used to derive and solve the equations of motion in the simulations. The equations of motions were determined from a reduced set of relative joint coordinates using one of two available methods. *Motion* employed either an enhanced version of *Kane's Method* or utilized an *Order (n)* formulation. The exact equations of motion were then implemented using *Symbolic Equation Manipulation.* This involved the manipulation of algebraic symbols as well as numerical values to simplify the equations of motion before their use in the analysis (Chang, 1997).

The individual simulations involved analyzing the motion of the rider from the initial configuration to the terminal condition. The initial configuration was as defined above and the terminal condition was when the rider's hip impacted the snow. Ankle deflection was measured as the angular deflection of the ankle from its equilibrium position (initial condition). This angle was positive when the trunk moved toward the nose of the board. The maximum ankle deflection was defined as the largest deflection that the ankle underwent during a simulation.

The goal of the sensitivity analysis was to determine the set of parameter values for all variable model parameters that gave the maximum sensitivity for a particular parameter. The variable model parameters were the snow stiffness and damping, the board stiffness, the rider mass/inertia, and the boot stiffness. The sensitivity was defined as the change in the maximum ankle deflection over the full range of the parameter of interest.

To determine maximum sensitivities, all parameters were initially set at their reference values (Table 2). Then the parameter of interest was selected (e.g., boot stiffness). Beginning with another parameter (e.g., snow stiffness), the sensitivity to the parameter

Table 1 Snowboarder anthropometric parameter values as indicated in Fig. 1 for the reference case

Segment	Mass	Moment of Inertia	Center of Gravity Distance
Torso/Head/Arms	m_{tr} = 41.326 kg	I_{tr} = 9.052 kg-m^2	d_{tr} = 0.438 m
Pelvis	m_p = 10.948 kg	I_p = 0.291 kg-m^2	L_l = 0.942 m
Leg	m_l = 12.415 kg	I_l = 1.005 kg-m^2	d_l = 0.552 m
Snowboard	m_b = 3.353 kg	I_b = 0.761 kg-m^2	d_b = 0.825 m d_{af} = $L_p/2$ = 0.250 m

Table 2 Parameter reference values and ranges

	Snow Stiffness	Snow Damping	Boot Stiffness	Board Stiffness	Mass & Inertia
Reference Value	10,000 N/m	1,000 Ns/m	500 Nm/rad	1,450 N/m	77.1 kg
Parameter Range	1,000-15,000 N/m (linear) 1,000-15,000 N/m^2 (quadratic)	300-2,000 Ns/m	0-1,000 Nm/rad (linear) 0-1,000 Nm/rad^2 (quadratic)	500-4,500 N/m	63.5 kg - 90.7 kg

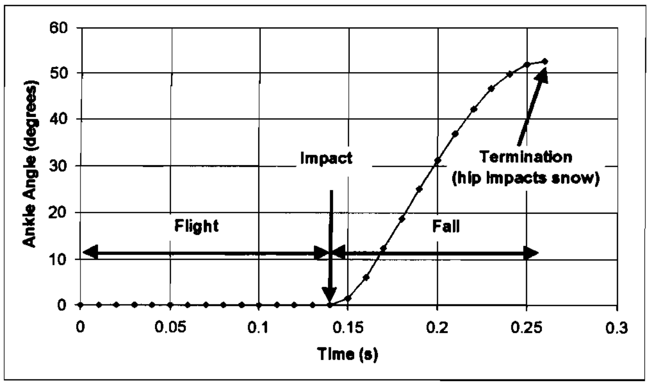

Fig. 3 Instantaneous ankle deflection for the reference case

Table 3 Results of sensitivity analysis

	Snow Stiffness	Snow Damping	Boot Stiffness	Board Stiffness	Mass & Inertia
Maximum Sensitivity (deg)	15.5	20.5	36.4	8.5	8.0
Number of simulations	65	75	70	70	81
Parameter values resulting in maximum sensitivity					
Snow Model	Linear	Linear	Linear	Linear	Linear
Snow Stiffness		0 N/m	15,000 N/m	15,000 N/m	15,000 N/m
Snow Damping	300 Ns/m		2,000 Ns/m	300 Ns/m	2,000 Ns/m
Boot Model	Linear	Linear	Linear	Linear	Linear
Boot Stiffness	0	0		1,000 Nm/rad	600 Nm/rad
Board Stiffness	4,500 N/m	500 N/m	500 N/m		500 N/m
Mass/Inertia	90.7 kg	90.7 kg	63.5 kg	90.7 kg	

of interest was computed while the second parameter value was varied by stepwise increasing its value from the minimum over its full range. The value of the varied parameter that gave the maximum sensitivity was recorded. Using that maximum sensitivity value now substituted for the reference value, a third parameter was varied over its full range. The value yielding the maximum sensitivity was substituted for the corresponding reference value. This procedure of substituting maximum sensitivity values for reference values and then performing a subsequent sensitivity analyses on the parameter of interest using the reference values of parameters not yet studied was repeated until all parameters had been included. The result was the set of values that gave the maximum sensitivity for the parameter of interest. For those parameters where more than one model form was of interest (e.g., linear or quadratic), the model form was also checked to see which gave the higher sensitivity. Because this procedure assumes that there is negligible interaction between parameters, this assumption was checked by computing sensitivities for the parameter of interest using parameter sets other than those identified as being maximum.

To insure that the maximum sensitivities given through the above procedure would be applicable to the broad spectrum of conditions encountered in practice, the parameters were varied over a wide range of values. In the case of the snow stiffness, the low value of zero corresponded to deep powder while the upper value of 15,000 N/m was 50 percent greater than the value for hard pack given by Mellor (1977). The snow damping was varied from one-third to twice the reference value. The lower and upper limits of the board stiffness were 33 and 300 percent of the reference value, respectively. The upper bound on the boot stiffness of 1000 N/m is the maximum flexion stiffness of Alpine ski boots measured by Bally et al. (1989) while the lower bound of zero is the passive ankle stiffness alone. Finally, the rider's mass/inertia was varied by creating riders of equal stature but with both lighter and heavier builds in addition to the average build (three lighter and three heavier). To create these builds, the segmental mass and inertia properties were scaled using the technique described by Forwood et al. (1985).

Results

The results for a typical simulation where the independent parameters were set to their reference values indicated that 140 ms elapsed during the flight phase prior to impact (Fig. 3). In this example, peak ankle deflection coincides with the termination of the simulation at 260 ms, which is when the rider's hip struck the snow. Accordingly, the time for the ankle to reach maximum deflection following impact was 120 ms.

Of the five parameters studied in the sensitivity analysis, the maximum ankle deflection had the greatest sensitivity to variation in boot stiffness over the range tested (Table 3). This sensitivity was more than 1.5 times greater than that of the snow damping, more than two times greater than that of the snow stiffness, and more than four times greater than that of both the board stiffness and inertia. The maximum sensitivity to boot stiffness occurred for the linear snow and boot stiffness models. Also, the sensitivity to boot stiffness increased with increasing snow stiffness and damping and with decreasing board stiffness and mass/inertia. For the set of parameter values that gave the maximum sensitivity, not surprisingly the ankle deflection decreased as the stiffness of the boot increased (Fig. 4).

The sensitivities to snow stiffness and damping were comparable, with the sensitivity to the damping being the higher (Table 3). As with the boot stiffness, the linear models produced greater sensitivity than the quadratic models. Although the sensitivity for each parameter increased with decreases in the other parameter, the sensitivity to the snow stiffness increased with increasing board stiffness while the sensitivity to the snow damping increased with decreasing board stiffness. Sensitivities to both parameters increased with increasing mass/inertia. The ankle deflection increased when either the snow stiffness (Fig. 5) or the snow damping (Fig. 6) increased.

The maximum sensitivities to the snowboard stiffness and mass/inertia were nearly identical for the ranges of parameter values studied (Table 3). Although both maximum sensitivity parameter sets included the greatest snow stiffness, the board stiffness set included the smallest snow damping value while the mass/inertia set included the largest damping value. Sensitivity to board stiffness increased with increases in both boot stiffness and mass/inertia while sensitivity to mass/inertia increased with decreases in board stiffness. Unique to the sensitivity for mass/inertia was the result that sensitivity was greatest

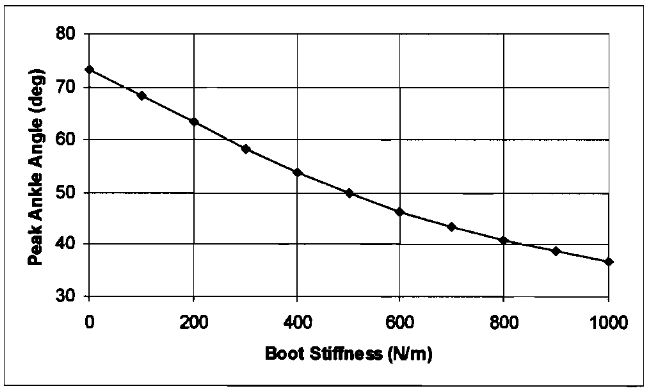

Fig. 4 Peak ankle deflection versus boot stiffness for the maximum sensitivity set of parameter values

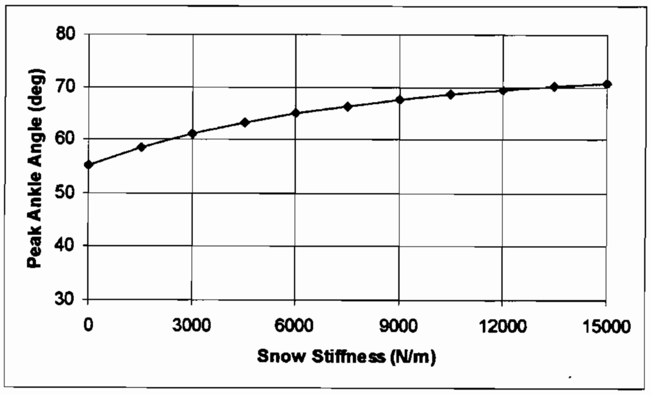

Fig. 5 Peak ankle deflection versus snow stiffness for the maximum sensitivity set of parameter values

for a value of boot stiffness that was not at either limit of the range. Although not shown in any figure, the peak ankle deflection increased with increases in both board stiffness and mass/inertia.

Discussion

Assumptions. Motivated by the desire to understand how the rider, equipment, and environmental factors affect snowboarding ankle injuries, a dynamic system model of a snowboarder was developed and used to study ankle deflection during a forward fall. The system model consisted of the rider, the boot/ankle, the snowboard, and the snow as components. Various assumptions were made for each component and merit critical examination.

A parallelogram linkage was used to model the rider and it consisted of the two legs, the board, and the pelvis/trunk as the four links. One key assumption of this model was that no motion occurred at the knee joint. During the course of a fall, the rider could potentially bend at the knees, which would influence the fall dynamics. However, if the snowboarder remains facing perpendicular to the "falling" plane, then the motion of the knee is minimized.

The trunk, arms, and head were lumped together as a single link for the parallelogram model, which could also affect the fall dynamics. Thus the individual contribution of the arms and head to the fall dynamics was assumed to be small compared to the overall influence of the torso. Both Webster and Brown (1996) and Gerritsen et al. (1996) made similar assumptions while modeling an Alpine skier.

One final assumption surrounding the parallelogram linkage model was that the fall was restricted to the "falling" plane.

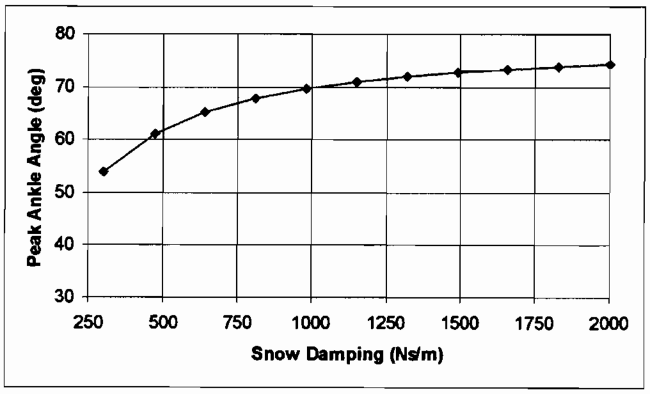

Fig. 6 Peak ankle deflection versus snow damping for the maximum sensitivity set of parameter values

Implicit to the assumption was that the rider would not twist such that the fall would become three dimensional. Although the torso of the rider may be twisted initially, as long as the CG's of the body segments lie in the falling plane at the time of impact, the impact forces will not develop moments about any axes other than that perpendicular to the falling plane. With only this moment developed, the motion will be restricted to the falling plane, in which case a two-dimensional model is appropriate.

Although a two-dimensional model may be appropriate for a forward fall, this fall scenario only represented a single fall. There is an infinite number of falls that could produce the injuries in question, but it would be an insurmountable task to model every fall. For this project, a fall was chosen based on inferences made from the epidemiology and from the authors' experience as a likely candidate to result in injurious motions of the ankle.

Although previous simulations of landings from a jump in Alpine skiing (Webster and Brown, 1996; Gerritsen et al., 1996) omitted passive ankle stiffness in the skier model, due to the higher flexibility of most snowboard boots, the passive ankle stiffness plays an important role in the snowboarder model and was included. As mentioned previously, cubic equations describing the passive ankle stiffness functions were obtained from best fits of experimental data from Chen et al. (1988); however, the range of motion encountered in the simulations exceeded their data. The key assumptions for the simulations were that the ankle did not fail and extrapolating the equations beyond the actual data limits gave a useful estimate of the ankle stiffness.

Due to the uncertainty of estimating ankle stiffness from the extrapolated equations, the sensitivity of the maximum ankle deflection to the passive ankle stiffnesses was studied. Beginning with the torque-rotation relations developed by Chen et al. (1988), the torque values were either halved or doubled (effectively halving or doubling the stiffness). The flexion and inversion/eversion stiffnesses were evaluated independently and the stiffness not in question was left at its original value. In both cases, all reference parameter values were used and the effect on the maximum ankle deflection was negligible (less than 0.5 deg change).

As in this study, Webster and Brown (1996) did not include any torques due to musculature; however, Gerritsen et al. (1996) included the effects of the musculature in protecting the ACL during a fall in skiing. Based on the time simulation of the average height model incorporating only the passive components of the ankle stiffness, the durations of both the flight phase and falling phase were approximately equal at 125 ms (Fig. 3). It is conceivable that muscles in the triceps surae group could develop force during either of these phases as a consequence of reflex mechanisms. If this occurred, then the ankle deflection would be decreased generally because the muscle moments would act to support the joint. Thus, not including the effects of the musculature in the analysis gave the worst case ankle deflection.

The boot model consisted of only a stiffness element and ignored any dissipative effects that the boots may have. This was the first time snowboard boots were modeled as far as the authors knew and neither data nor models were available for the dissipative action of snowboard boots. Including a dissipative element in the boot model would affect the restoring torque and would most likely affect the ankle deflection. Studies of Alpine ski boot load-deflection have shown evidence of hysteresis (Yee and Mote, 1993). Gerritsen et al. (1996) used a dissipative element representing dry friction while modeling a ski boot.

An assumption specific to the snowboard boot model was its lack of a flexion stiffness component; only the inversion/eversion component was included. In the model, only the forward ankle experienced dorsiflexion during a forward fall. In addition, snowboard boots generally are designed with flexibility in dorsiflexion to facilitate rider mobility; in fact, even hard boots offer significant flexibility in this regard. However, if one were to model a backward fall, then the flexion stiffness would become critical because snowboard boots coupled with the bindings offer significant resistance to plantarflexion.

Similar to studies that simulated Alpine skiers landing from a jump (Webster and Brown, 1996; Gerritsen et al., 1996), the model included the flexibility of the board. Preliminary analyses that treated the board as rigid gave different trends in sensitivity than analyses where the board flexibility was included. Thus, representing the flexibility of the board in the model was important.

Interpretation. Before proceeding with the interpretation, it should be recognized that the approach used for the sensitivity analysis deviated from the formal mathematical approach where the partial derivatives of the dependent variables (i.e., maximum ankle deflection) are computed with respect to the independent variables (i.e., snow stiffness, snow damping, ankle stiffness, etc.) about specific sets of values for the independent variables. Using the partial derivative as a measure of sensitivity is appropriate for applications where small deviations about some set of reference values are of interest because the functional relationship between dependent and independent variables is approximately linear. However, in this application, the independent variables varied over a wide range and the relationships between the dependent variable and the independent variables were strongly nonlinear (Figs. 4, 5, and 6). Accordingly the range of maximum ankle deflection computed over the full range of each independent variable, rather than the partial derivative, was used as the measure of sensitivity. This alternative measure of sensitivity gave a ready appreciation for the importance of each of the independent variables to the model response without the need to qualify results about a set of reference values. Because of the nonlinear relationships, this appreciation would not have been possible from partial derivatives.

Within the context of the assumptions outlined above, the results can be assessed in relation to the project objective, which was to determine the importance of various model parameters. The modeling of the snow had important effects because of its direct relationship to the impact forces. The sensitivities showed that increases in both the snow stiffness and snow damping resulted in increased ankle deflections of up to 20 deg. The sensitivity to both stiffness and damping parameters suggests the need to determine these parameters collectively for each snow condition of interest. Inasmuch as the snow stiffness was varied over a much larger range than the snow damping yet the sensitivity to snow damping was greater, it is more important to obtain an accurate measure of snow damping for the specific condition of interest.

While including the board stiffness was important to the computation of ankle deflections, the sensitivity analysis to the board stiffness indicated that varying the stiffness over a wide range (30 to 300 percent) around the measured stiffness of 1450 N/m did not affect ankle deflections. Thus, the results of the simulation were not sensitive to the board stiffness. Because of this low sensitivity, future studies of ankle deflection can be simplified by using only a single representative value for board stiffness.

The sensitivity analysis demonstrated a second useful result in guiding future studies: namely, for individual sizes, the effect of build can be discounted as an independent variable of importance. However, it would still be useful to explore the effects of rider size over a range of sizes rather than the single size used here. This is because snowboarding is popular among adults and children alike. Presumably a wide range of rider sizes would create some significant sensitivity.

The role played by the boot stiffness in limiting maximum ankle deflection was of particular interest since this can be controlled in the boot design process. For the two boot models studied, the maximum ankle deflection was sensitive to changes in the boot stiffness but the sensitivities of the two models differed from each other. Although the linear boot model showed a greater reduction in the ankle deflection and hence greater sensitivity than did the quadratic model, the results from both models emphasize the benefit of a stiff boot in reducing ankle deflection. Accordingly, the results of this analysis confirm the anecdotal evidence cited in epidemiology studies that riders using soft boots are more susceptible to ankle injuries (Bladin et al., 1993). Given this susceptibility and the results from this study, which demonstrated high sensitivity of peak ankle deflection to boot stiffness, it would appear worthwhile to limit ankle deflection through judicious design of the boot.

As in the present study, Webster and Brown (1996) investigated the role that boot stiffness played in ankle deflection, and they reached similar conclusions, although the details of their analysis were different. Both studies agreed that the boot stiffness played an important role in the maximum ankle deflection; however, Webster and Brown (1996) addressed pure flexion since their model was of a skier. Here, the "falling" plane definition of ankle deflection included inversion/eversion along with flexion.

Conclusions

1 Of all the parameters studied, the maximum ankle deflection was most sensitive to the stiffness of the boots. This high sensitivity suggests that a worthwhile direction of development in snowboard boots would be a design that offers a reasonable compromise between the flexibility necessary for maneuvers and the stiffness needed to mitigate ankle injuries.

2 Although lower, the sensitivity of the peak ankle deflection to the snow model parameters was still significant, being roughly half of the boot sensitivity. The relatively high sensitivity to both stiffness and damping parameters suggests that an accurate model for the snow is important to develop a comprehensive model with which to make worthwhile conclusions over the full range of realistic snow conditions.

3 The peak ankle deflection was relatively insensitive to the variation of the rider's mass/inertia and the stiffness of the board. Accordingly future studies of ankle deflection can be simplified by focusing on the more important model components such as the snow.

References

Aitkens, M., 1990, "Have Snowboard, Will Soar," *The Physician and Sportsmedicine,* 18: 114–121.

Abu-Laban, R. B., 1991, "Snowboarding Injuries: An Analysis and Comparison With Alpine Skiing Injuries," *Canadian Medical Association Journal,* 145: 1097–1103.

Bally, A., Boreiko, M., Bonjour, F., and Brown, C. A., 1989, "Modeling Forces on the Anterior Cruciate Knee Ligament During Backward Falls While Skiing," in: *Skiing Trauma and Safety: Seventh International Symposium,* ASTM STP 1022, M.-H. Binet, C. D. Mote, Jr., & R. Johnson, eds., American Society for Testing and Materials, Philadelphia, pp. 267–275.

Bladin, C., Giddings, P., and Robinson, M., 1993, "Australian Snowboard Injury Database Study, A Four Year Perspective," *The American Journal of Sports Medicine,* 21: 701–704.

Chang, C., 1997, *Pro/MECHANICA Getting Started With Motion,* Release 18, Parametric Technology Corporation.

Chen, J., Siegler, S., and Schneck, C. D., 1988, "The Three Dimensional Kinematics and Flexibility Characteristics of the Human Ankle and Subtalar Joint—Part II: Flexibility Characteristics," ASME JOURNAL OF BIOMECHANICAL ENGINEERING, 110: 374–385.

Forwood, M., Neal, R., and Wilson, B., 1985, "Scaling Segmental Moments of Inertia for Individual Subjects," *Journal of Biomechanics,* 18: 755–761.

Ganong, R. B., Heneveld, E. H., Beranek, S. R., and Fry, P., 1992, "Snowboarding Injuries, A Report of 415 Patients," *The Physician and Sportsmedicine,* 20: 114–122.

Gerritsen, K. G. M., Nachbauer, W., and van den Bogert, A. J., 1996, "Computer Simulation of Landing Movement in Downhill Skiing: Anterior Cruciate Ligament Injuries," *Journal of Biomechanics,* 29: 845–854.

Mellor, M., 1977, "A Review of Basic Snow Mechanics," Snow Mechanics Symposium, International Association of Hydrological Series, Publication No. 114.

Pino, E. C., and Colville, M. R., 1989, "Snowboard Injuries," *The American Journal of Sports Medicine,* 17: 778–781.

Robinson, M., 1991, "Hazards of Alpine Sport," *Australian Family Physician,* 20: 961–970.

Schaff, P. S., and Hauser, W., 1993, "Influence of Ski Boot Construction on Knee Load—A Biomechanical Investigation on Safety and Performance Aspects of Ski Boots," in: *Skiing Trauma and Safety: Ninth International Symposium,* ASTM STP 1182, Robert Johnson, C. D. Mote, Jr., and John Zelcer, eds., American Society for Testing and Materials, Philadelphia, pp. 75–88.

Webster, J. D., and Brown, C. A., 1996, "Computer Simulation of the Loads on the ACL During Backward Falls Based on an Open Kinematic Chain Model While Skiing," in: *Skiing Trauma and Skiing Safety: Tenth Volume,* ASTM STP 1266, C. D. Mote, Jr., R. J. Johnson, W. Hauser, and P. Schaff, eds., American Society for Testing and Materials, Philadelphia, pp. 254–269.

White, D., 1995, "Utah Holdouts Cracking, As Solitude Approves Early Week Boarding," *Transworld Snowboarding,* 8.

Winter, D. A., 1990, *Biomechanics and Motor Control of Human Movement,* Ch. 3, Anthropometry, Wiley, New York.

Yee, A. G., and Mote, C. D., Jr., 1993, "Skiing Forces and Moments at the Knee & Boot Top: Boot Stiffness Effects and Modeling," in: *Skiing Trauma & Safety: Ninth International Symposium,* ASTM STP 1182, Robert J. Johnson, C. D. Mote, Jr., and John Zelcer, eds., American Society for Testing and Materials, Philadelphia, pp. 111–127.