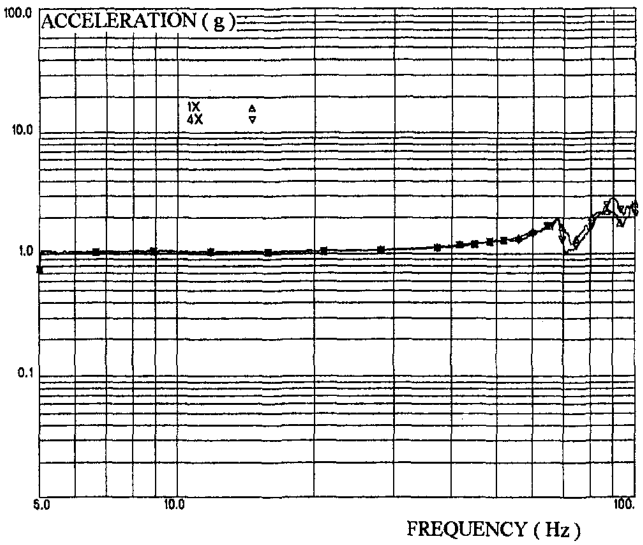

Fig. 8 *X* **axis responses for locations 1 and 4 for 1g input in** *X* **axis**

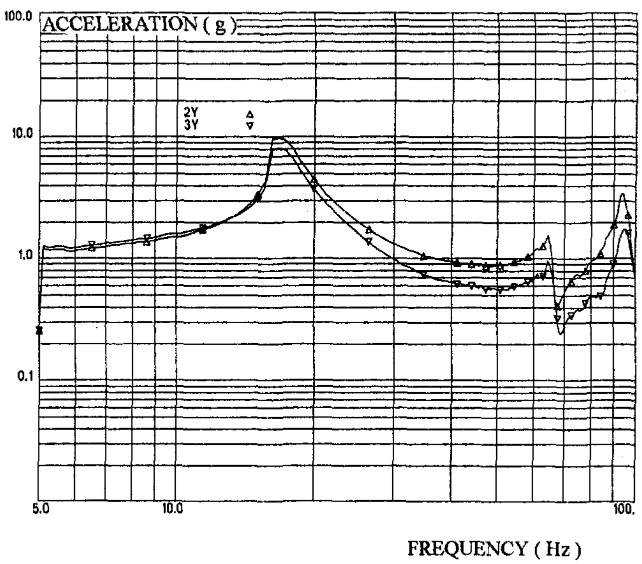

Fig. 9 *Y* **axis responses for locations 2 and 3 for 1g input in** *X* **axis**

door assembly, so an estimated damping ratio of 0.02 was used.

5 Conclusions

The door assembly was designed and modelled within the given low mass budget. It survived the vibration tests which simulate the launch environment. These tests qualified the design for the flight structure. The door opening test which followed the vibration was satisfactory in that all the components of the door mechanism operated successfully.

References

1. Mahmoud, S., 1993, JET-X Door Assembly FE Model, April, Space Research Group-University of Birmingham.

2. Private communications with X-ray Astronomy Group, 1990, University of Leicester.

3. Aeroweb Type 5052, Ciba-Geigy data sheet No. ATA.20f, Sept. 1989. Bonded Structures Ciba-Geigy Plastics.

4. Morris, N., 1993, JET-X STM Qualification Vibration and Shock Test Report, JET-X(93)RAL-144, Issue: 1, July, Rutherford Appleton Laboratory.

Electromechanical Ski Release Binding With Mechanical Backup

M. L. Hull,[1] M. Swanstrom,[2] and B. Wade[3]

To better protect Alpine skiers against injuries to both the lower leg and the knee, the objective of this work was to design a binding which: (1) maintained a consistent release level in twist in the presence of combined loads; (2) released the heelpiece based on the anterior/posterior (A/P) bending moment transmitted by the leg; and (3) modulated the release level in twist depending on the degree of contraction in muscles crossing the knee. To fulfill the objective, a conventional ski binding was modified. Modifications included integrating dynamometers into the toepiece, anti-friction device (AFD), and heelpiece. The toepiece sensor indicates the twisting moment while the AFD and heelpiece sensors indicate the anterior bending moment transmitted by the leg. To gain electronic control of binding release, a solenoid actuated mechanism was added which translated the heelpiece rearward along the ski to decouple the boot from the binding. Otherwise, the binding allowed normal mechanical function. Prototype testing confirmed the ability of the dynamometers to accurately measure desired loads in the presence of extraneous loads and the reliability of the solenoid actuated mechanism in releasing the boot under loads typical of skiing. Thus, this work demonstrated the feasibility of hybrid electromechanical/mechanical releasable bindings. Such a demonstration should encourage the development of designs for commercial use.

Introduction

Knee injuries in Alpine skiing persist (Young and Lee, 1991) because current bindings have limitations in achieving timely release when the leg is subjected to either twisting or anterior bending, two actions that are often associated with knee injuries (Shino et al., 1987). Achieving timely release requires that the binding limit the loads transmitted to the lower leg and knee. However, release torques in twist significantly increase for commercially available bindings when a combined moment about the long axis of the ski is applied (Greenwald, 1995). Inasmuch as this combined moment is routinely developed in skiing (Wunderly et al., 1988), inconsistent release in the twist mode under combined loading is of practical concern.

A second limitation in the twist mode concerns the fixed release level. Although the strength of the knee is dependent on the amount of contraction in the surrounding musculature and the knee flexion angle (Louie and Mote, 1987; Hull and Johnson, 1989), current bindings have a fixed release level which is preset according to standards such as ASTM F939-93 (ASTM, 1996) with the goal of satisfying the retention requirement. A level which is sufficient to satisfy the retention requirement may exceed the strength of the knee particularly when it is unweighted (Piziali et al., 1982; Hull and Johnson, 1989). Therefore, the release level in twist may need to be modulated to correspond with the instantaneous knee strength.

A third limitation is that current bindings use the upward force at the heel as an indicator of the anterior bending moment in the knee and lower leg, but the correlation between this force

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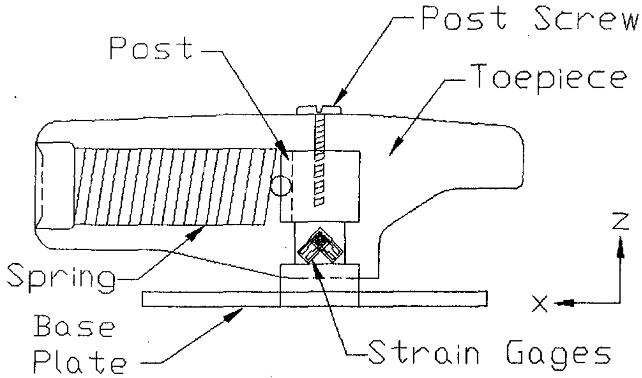

Fig. 1 ***Toepiece Dynamometer.*** **The dynamometer measures the torsion developed in the post by the lateral boot toe force which is *y*-directed.**

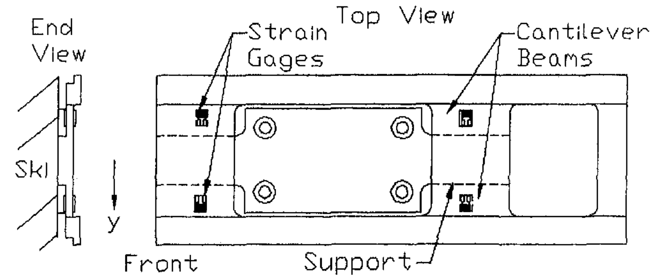

Fig. 3 ***Heelpiece Dynamometer.*** **The dynamometer measures the boot-binding contact force component normal to the ski surface.**

and the bending moment at the injury site is low (Quinn and Mote, 1992). Therefore timely release in this mode cannot be expected.

The objective of this work was to modify the current binding design to overcome the limitations noted above, while keeping the binding as close to current designs as practical. The new design incorporates an electromechanical release and a mechanical backup in case of an electrical failure.

Design Description

The design is divided into four components—three transducers and the release mechanism. Shown to correlate strongly with the axial moment transmitted by the knee (Quinn and Mote, 1992), the lateral force at the boot toe was measured by the use of a standard LOOK (Model LN, Never, France) toepiece with some modification. The LOOK toepiece is mounted on a steel post, which does not allow rotation of the toepiece unless the lateral force reaches the release level. The torsional moment produced on the post when rotation is not allowed was used to indicate the lateral force. The transducer was created by mounting two 90 deg strain gage rosettes on opposite sides of the post and orienting them to measure torsion (Fig. 1). With the gages connected into a full Wheatstone bridge, the bridge signal was theoretically insensitive to both temperature and extraneous loads.

To indicate the anterior bending moment, the force normal to the boot sole was measured at both the toe and heel by two additional dynamometers. A linear combination of these two force components has been shown to correlate more strongly to the anterior bending moment at the injury sites (i.e., lower leg and knee) than the upwards force at the heel (Quinn and Mote, 1992). At the toe the standard anti-friction device (AFD) was modified to serve as both a force transducer and an AFD. Similar to Neptune and Hull (1992), the transducer consists of two small cantilever beams fitted with four strain gages to measure the strain due to bending (Fig. 2). A small Teflon strip placed along the boot contact region provides the AFD feature. When connected into a full Wheatstone bridge, the resulting transducer output is sensitive only to the bending due to the normal force and is independent of the location of the center of the pressure.

Because both the upward and downward heel forces are transmitted through the track typical of most modern heelpieces, the track was modified to serve as the transducer for these forces. The runners of the track are supported by four cantilevers which are in turn fixed to the ski by way of two supports (Fig. 3). One strain gage is mounted at the base of each cantilever, where two gages are on top of the beams and two are on the bottom. Arranging the gages in a full Wheatstone bridge where top (bottom) gages are in opposite arms creates a signal which is theoretically insensitive to both moments and forces in any direction except that desired.

Based on an electrical command issued by a controller processing dynamometer signals, an electromechanical mechanism translated the entire heelpiece backwards 2 cm to release the boot. The mechanism consisted of a standard heelpiece which was modified to slide freely on the track. Heelpiece motion is restricted by a linkage fixed to the back of the heelpiece (Fig. 4) when the binding is in the latched position. In this position, the link pin engages the latch so that the links are in a nearly straight but slightly over-center configuration. This configuration allowed the mechanism to support large axial forces developed as a result of boot compression.

When release is desired, a solenoid is activated thus disengaging the linkpin from the latch. This allows the linkage to collapse under the force of the main springs, thus translating the heel-

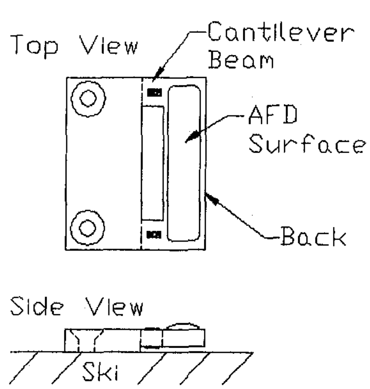

Fig. 2 ***AFD Dynamometer.*** **The dynamometer indicates the boot contact force normal to the AFD surface.**

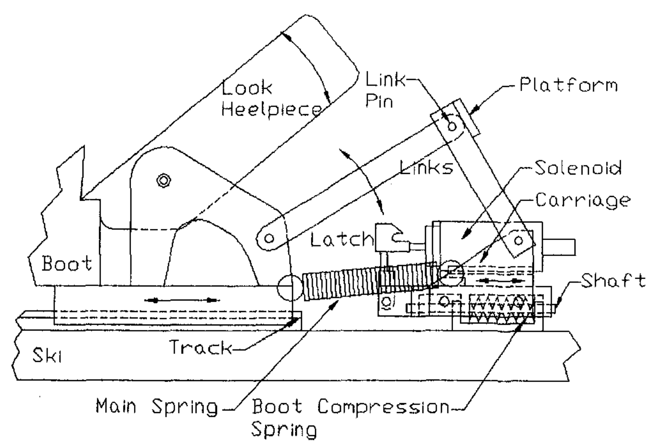

Fig. 4 ***Mechanism in the Unlatched Position.*** **To latch the binding, force is applied by the skier to the platform until the link pin engages the latch.**

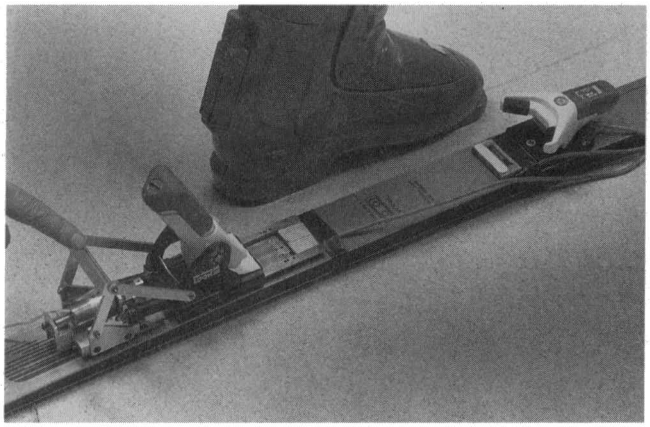

Fig. 5 ***Photograph of Prototype.*** **In the picture, the heelpiece is in the latched position and the electromechanical mechanism is in the unlatched position. The boot is removed so that the AFD dynamometer can be visualized.**

piece back the required 2 cm (Fig. 4). The restoring force of the main springs is 175 N initially. Resetting of the mechanism after release is achieved by stepping on the platform attached to the linkage joint. The maximum force required to reset is 180 N which can easily be applied by any skier weighing more than 360 N. Longitudinal elasticity was maintained by mounting the solenoid on a carriage connected to the ski by springs.

Prototype Testing

A prototype (Fig. 5) was constructed and subjected to three types of tests. One test was a static calibration of the dynamometers where both direct sensitivity to the force component of interest and cross sensitivity to the remaining two extraneous force components were determined. For all dynamometers, the points of load application coincided with those of the boot-binding reaction loads so that realistic force-moment combinations were developed at the gaged cross-sections. Loads were applied incrementally and a regression analysis was done to determine the calibration coefficients.

The direct sensitivities of all dynamometers were much greater than the cross-sensitivities. The direct sensitivity to the lateral boot toe force Fy was more than 100 times greater than the cross-sensitivity to either the longitudinal force Fx or the force normal to the ski Fz. For the AFD, the cross sensitivities to Fx and Fy were at least 5 and 100 times lower respectively than the direct sensitivity to Fz. Also the direct sensitivity was virtually independent of the transverse variation in the center of pressure for the AFD (Neptune and Hull, 1992). The direct sensitivity to Fz at the heel was at least 20 times greater than the cross sensitivities to either Fx or Fy. Also the direct sensitivity varied less than 10 percent and 1 percent to transverse and longitudinal variations respectively in the center of pressure.

Each of the dynamometers was also calibrated dynamically by measuring the natural frequency in the mode corresponding to the direct sensitivity. The natural frequencies were 500 Hz, 2300 Hz, and 230 Hz for the toe, AFD, and heel dynamometers respectively. Because the flat response region is 22 percent of the natural frequency and the upper limit of the frequency content is about 50 Hz (Hull and Mote, 1978), these natural frequencies are satisfactory for accurate measurement of dynamic loads.

The time delay of the release mechanism in releasing the boot was measured by loading a boot installed in the binding assembly, actuating the solenoid, and simultaneously recording the dynamometer output as a function of time. To assess any dependence of release function on load magnitude, loads were applied at various levels up to a maximum of 250 Nm and 80 Nm for forward bending and torsion respectively. A varying vertical force up to 667 N was applied in conjunction with the torsional moment. The time delay until the dynamometer reached 50 percent of its initial value was in the range 15–20 ms and was insensitive to the various applied loads.

Discussion

Although the processing scheme and the electronic controller are integral aspects of the binding system, these aspects were not addressed in this work. This is because controllers presented previously by either Lieu and Mote (1980) or Neptune and Hull (1992) could be easily modified to complete the system. However, the processing scheme for release level modulation in twist is a topic of current research (e.g., Crawford and Mote, 1996). Nevertheless, even without the release level modulation capability, the binding system presented here would still offer skiers immediate safety benefits over current mechanical bindings in gaining consistent release in twist and release sensitivity to anterior bending moments in the leg.

To meet the design criteria, the accuracy of the dynamometers was an important issue. Although the static calibration results suggest that the dynamometers would accurately measure the loads of interest because of the small cross-sensitivities for extraneous loads, the cross sensitivities must be considered in conjunction with the maximum expected extraneous loads to fully interpret the information in the tables. Inasmuch as this interpretation was made in another article (Hull et al., 1996), it will not be repeated here. The result was that the worst case full scale error was 2 percent. This result in conjunction with the minimum natural frequency of 230 Hz establishes the accuracy of the dynamometers over the full range of expected loading bandwidth.

Another important issue was the time delay to binding release following the electrical command. Inasmuch as loading times to binding release have been measured as short as 50 ms during actual skier falls (Hull and Mote, 1978), it is clear that a 10 to 20 ms delay could allow loading to build to a dangerous level. Thus for high loading rate situations, the skier's protection would be provided by the mechanical backup.

Operational convenience was an important consideration. To lock the boot into the binding following electromechanical release, the electromechanical release must first be latched followed by stepping into the binding to latch the heel. Although this requires two actions on the part of the operator as opposed to a single action, each action may be performed with the foot thus avoiding any manual operation.

Both the size and weight were a final concern. Although the total length of the heel mechanism was extended by 15 cm, the weight increase was kept to only 0.36 kg by using predominantly lightweight aluminum parts. This weight increase is less than 10 percent of a single ski-boot-binding system.

Acknowledgment

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References

ASTM, 1996, "Selection of Release Torque Values for Alpine Ski Bindings," 1996 Annual Book of ASTM Standards Section 15, American Society for Testing and Materials, Philadelphia, PA, Vol. 15.07, ASTM Standard F939-93.

Crawford, P., and Mote, C. D., Jr., 1996, "Fuzzy Logic Control of Bioadaptive Ski Binding Release," *Skiing Trauma and Safety: STP 1266,* Mote, C. D., Jr., Johnson, R. J., Hauser, W., and Schaff, P., eds., American Society for Testing and Materials, Philadelphia, PA, pp. 323–338.

Greenwald, R. M., 1995, "Variations in Binding Release Torques Under Modified ASTM Testing Conditions Using a Static Preload Torque," 11th International Symposium on Skiing Trauma and Safety, Voss, Norway, April 1995.

Hull, M. L., and Johnson, C., 1989, "Axial Rotation of the Lower Limb Under Torsional Loading: I. Static and Dynamic Measurements in Vivo," *Skiing Trauma* *and Safety: STP 1022,* American Society for Testing and Materials, Philadelphia, PA, pp. 277–290.

Hull, M. L., and Mote, C. D., Jr., 1978, "Analysis of Leg Loading in Snow Skiing," ASME *Journal of Dynamic Systems, Measurement, and Control,* Vol. 100, pp. 177–186.

Hull, M. L., Swanstrom, M., and Wade, B., 1996, "Electromechanical Ski Binding with Mechanical Backup," to appear in *Skiing Trauma and Safety:* STP 1289, American Society for Testing and Materials, Philadelphia, PA.

Johnson, R. J., Ettlinger, C. F., and Shealy, J. E., 1993, "Skier Injury Trends—1972–1990," *Skiing Trauma and Safety: STP 1182,* American Society for Testing and Materials, Philadelphia, PA, pp. 11–12.

Lieu, D. K., and Mote, C. D., Jr., 1980, "An Electronic Ski Binding Design with Biofeedback," ASME Journal of Mechanical Design, Vol. 102, pp. 677–682.

Louie, J. K., and Mote, C. D., Jr., 1987, "Contribution of the Musculature to Rotary Laxity and Torsional Stiffness at the Knee," *Journal of Biomechanics,* Vol. 20, pp. 281–300.

Neptune, R., and Hull, M. L., 1992, "A New Electromechanical Ski Release Binding with Release Sensitivity to Torsion and Bending Moments Transmitted by the Leg," *International Journal of Sport Biomechanics,* Vol. 18, pp. 331–349.

Piziali, R. L., Nagel, D. A., Koogle, T., and Whalen, R., 1982, "Knee and Tibia Strength in Snow Skiing," *Skiing Trauma and Skiing Safety IV,* TUV, Munich, pp. 24–31.

Quinn, T. P., and Mote, C. D., Jr., 1992, "Prediction of the Loading Along the Leg During Snow Skiing," *Journal of Biomechanics,* Vol. 25, pp. 609–625.

Shino, K., Horibe, S., Nagano, J., and Ono, K., 1987, "Injury of the Anterior Cruciate Ligament of the Knee in Downhill Skiing: Its Pathomechanism and Treatment," *Skiing Trauma and Safety: STP 938,* American Society for Testing and Materials, Philadelphia, PA, pp. 68–86.

Wunderly, G., Hull, M. L., and Maxwell, S. M., 1988, "A Second Generation Microcomputer Controlled Binding System for Alpine Skiing," *Journal of Biomechanics,* Vol. 21, pp. 299–318.

Young, L. R., and Lee, S. M., 1991, "Alpine Injury Pattern at Waterville Valley—1989 Update," *Skiing Trauma and Safety: STP 1104,* American Society for Testing and Materials, Philadelphia, PA, pp. 125–132.