

Article

Testing and Experimental Research on the Flexural Stiffness of Alpine Ski Boots Based on Buckling Mechanical Characteristics

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Abstract

Existing buckling stiffness tests usually load the ski boot in a manner that changes with the buckling angle of the boot cuff. As a result, the direction of the applied force changes as the cuff bends, which can cause a deviation between the measured force and the actual acting force and can influence the test result. In this study, a new buckling stiffness test device was designed and constructed. By introducing a translational-rod loading structure, the device keeps the loading force perpendicular to the prosthetic-foot loading rod throughout the test. Tests were conducted at a room temperature of 15 °C, with a fixed force-arm length of $L = 0.31$ m and a standard binding tension of $F = 40$ N, thereby improving the consistency of load-angle measurement. A binding-force adjustment unit was also designed through computer-aided design, and the standard binding force was determined through subjective comfort tests involving 20 skiers, enabling consistent control of the tightness state of the ski boot. Theoretically, the expression for ski-boot buckling stiffness was established using an equivalent torsional-spring model. Under small-angle and quasi-static conditions, the equivalent buckling stiffness was represented as a linear relationship between the applied load and the normalized deflection angle. The experimental results show that, within the loading range of 60–260 N, the relationship between load and deformation exhibited good linearity, with coefficients of determination of 0.986–0.996. Repeatability tests showed that the coefficients of variation of load and deflection-angle measurements were controlled within 0.40–1.48% and 6.92–8.26%, respectively, and the relative expanded uncertainty of equivalent buckling stiffness was 7.33–11.93%. These results indicate that the device has good stability. Although the fitted curves showed slight nonzero intercepts, these mainly originated from clamping error, contact effects, and sensor zero drift, and did not affect stiffness identification. Overall, the device can provide stable and reliable buckling stiffness measurement and offers an effective method for evaluating ski-boot performance.

Keywords: alpine ski boot; buckling stiffness; reliability; measurement accuracy



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1. Introduction

After the successful hosting of the 2022 Beijing Winter Olympic Games and the subsequent policies aimed at strengthening investment in the ice and snow industry, the ski industry in China entered a period of rapid growth and development. Despite this progress, research reports by Orient Securities emphasized that China remains relatively behind in the production and research of ski equipment and instruments. Therefore, the funded

research project discussed in this paper focuses on the design and construction of a buckling stiffness test device for alpine ski boots.

As a major item of equipment in skiing, the quality of a ski boot greatly affects skier safety, comfort, and control. Among these factors, ski-boot buckling stiffness is a key parameter affecting leg force transmission and comfort. It has a substantial influence on the overall motion experience and postural control of skiers [1]. Buckling stiffness is an index used to measure the resistance of a ski boot to bending and refers to the ability of the boot to withstand external force without deformation. Higher bending stiffness indicates less attenuation of force transmitted from the leg to the ski, but it may reduce comfort. Excessive buckling stiffness during skiing can intensify the interaction between the skier and the snow or ice surface, thereby increasing the potential risk of knee and ankle injuries [2,3]. In addition, ski boots with high buckling stiffness may place the skier in an upright or backward body position and seriously affect skiing safety [4]. Conversely, excessively low buckling stiffness may prevent the ski boot from effectively limiting ankle-joint motion, thereby affecting the skiing experience [5]. Low buckling stiffness may also delay force transmission and affect the separation of the leg from the ski, thereby influencing the safe release of the ski [6,7]. Therefore, selecting an appropriate buckling stiffness for ski boots is important for skier safety, maneuverability, and user experience.

In the field of ski-boot buckling stiffness testing, Lorenz Immler proposed that the optimal buckling stiffness is related to human skeletal characteristics, snow conditions, boot temperature, and other factors, indicating that ski-boot buckling stiffness significantly affects skiing speed [8]. Researchers from the University of Padua, including Nicola Petrone, developed a device for evaluating the influence of bending stiffness on the flexural behavior of alpine ski boots. The device was used both in field and laboratory environments. A prosthetic foot wore four pairs of ski boots with different buckling stiffness values, and the results showed that buckling stiffness significantly influenced the flexural behavior of ski boots [9]. Michael Hasler and Patrick Hofer developed a measurement system that can test the stiffness characteristics of ski boots at high ankle angular velocities [10]. They investigated the influence of angular velocity on ski-boot buckling stiffness and achieved a repeatability of 3%. However, as the bending angle increases, the direction of the loading force in that system may differ from the actual force direction acting on the prosthetic foot. This angular change affects result reliability because it changes the actual force applied to the foot. Similar to many other studies, the system could not control ski-boot binding tightness during actual testing, which negatively affected its reliability and accuracy.

To address these problems, this study designed a test device for measuring the buckling stiffness of alpine ski boots. The device constrains the loading path using a translational-rod loading structure, so that the externally applied load remains perpendicular to the prosthetic-foot loading rod throughout the test. This reduces error introduced by changes in force direction. A binding-force adjustment mechanism was also introduced to maintain a consistent constraint state during the experiment and reduce the influence of differences in strap tightness between samples. This structure improves the stability of measurement results and provides experimental conditions for subsequent research on the influence of binding force on stiffness test results.

The translational-rod loading mechanism designed in this study can effectively avoid deviation of the load-transfer path during testing and reduce the influence of additional loads on the test results at the structural level. In mechanical-property testing, fixture structural design, parasitic-load suppression, accurate load transmission, and consistent boundary-condition control are always important issues affecting test accuracy. If the fixture structure is unreasonable or if deviations occur during assembly, geometric errors and additional loads can easily be generated, reducing the accuracy and repeatability

of the test results. Therefore, the loading structure and the ski-boot clamping structure were optimized in this study to reduce interference caused by structural coupling and assembly error. Previous studies have shown that reasonable fixture design is important for improving the stability and reliability of mechanical test systems [11,12].

Unlike traditional loading methods, the translational-rod loading structure proposed in this paper maintains the applied load perpendicular to the prosthetic-foot loading rod throughout the entire test, thereby avoiding additional bending moments and measurement errors caused by changes in loading direction. This design is essentially an engineering application of classical mechanical test theory in specialized ski-equipment testing. Its core principle is consistent with the basic design concepts of a stable load path and controllable boundary conditions in mechanical experiments.

The device also includes a binding-force adjustment mechanism that allows precise control of the binding force and ensures a consistent ski-boot constraint state throughout the experiment. By maintaining a constant binding force, the device further improves the accuracy and repeatability of buckling stiffness measurement. The binding-force control mechanism can also be used to study the correlation between binding force and buckling stiffness, providing an experimental basis for analyzing the influence of binding state on the overall mechanical performance of ski boots.

It is worth noting that the use of a prosthetic foot in this study is consistent with established practices followed in many previous studies [13]. Following these practices helps ensure the validity and comparability of results obtained from the device. The remainder of this paper is organized as follows. Section 2 describes the theory behind buckling stiffness and presents the mathematical expression used to determine it. Section 3 introduces the alpine ski-boot bending stiffness test equipment and its main features. Section 4 evaluates the performance of the device using four types of ski boots and presents the reliability and accuracy of the test. Section 5 summarizes the findings and proposes potential directions for future research.

2. Determination of Buckling Stiffness

This section proposes a physically meaningful model for determining the bending stiffness of alpine ski boots. The model simplifies the test system into two parts: a rigid rod that simulates the lower leg and a torsional spring that simulates the bending effect of the boot cuff. During skiing, the skier flexes the ankle joint forward, causing the lower leg to apply a bending load to the ski-boot cuff and inducing forward deformation of the cuff. The degree of deformation directly reflects the ability of the boot to resist bending and can therefore be used to characterize buckling stiffness. To simulate this actual working condition under laboratory conditions, the human body-ski boot system must be mechanically simplified and modeled.

In a typical skiing posture, the skier leans slightly forward, and the ankle joint undergoes dorsiflexion within a limited angular range. According to ergonomic and skiing biomechanics studies, one leg usually bears approximately 60–80% of the body weight during skiing, while the remaining load is shared by the other leg and the snow-surface reaction force [14]. Assuming that the body mass of a skier ranges from 50 kg to 100 kg, the body weight is 490–980 N, and the corresponding single-leg equivalent load G can be taken as 300–800 N. Previous studies have shown that the forward-flexion angle of the ski-boot cuff during actual skiing and laboratory testing is generally within 10 degrees to 20 degrees [9,10,13]. In this angular range, the load applied by the lower leg to the boot cuff can be decomposed into a component along the lower-leg direction and a component perpendicular to the lower-leg direction. The latter is the main driving force causing bend-

ing deformation of the boot cuff. Therefore, the equivalent bending load F acting on the loading rod can be expressed as follows:

$$F = G \sin \alpha \quad (1)$$

where α is the included angle between the skier's tibia and the vertical direction. This equation is used only to justify the baseline laboratory test range of 60–260 N. The actual bending load on snow is much more complex and can be significantly higher. Under typical skiing conditions, the equivalent bending load F acting on the ski-boot cuff is approximately 50–300 N. This range can cover the actual bending action generated by skiers of different body weights in common skiing postures. Although ergonomic analysis indicates that the equivalent bending load range is approximately 50–300 N, the lower and upper boundaries correspond to very light body weight or a very small forward-flexion angle, and to very heavy body weight or an extreme forward-flexion posture, respectively. Near the lower boundary, the cuff deflection angle is small and the measurement signal-to-noise ratio is low. Near the upper boundary, the cuff may enter a nonlinear deformation stage, thereby affecting repeatability and the validity of the linear assumption. Therefore, a practical loading range of 60–260 N was selected in this study to cover typical human working conditions while ensuring measurement stability and reliability.

For mechanical analysis, the test system can be simplified into a rigid loading rod simulating the lower leg and an equivalent torsional spring representing the bending characteristics of the ski-boot cuff. The ski boot has a hinge at the ankle joint, but rotation is achieved through deformation of the cuff. The cuff is made of thermoplastic polyurethane. Within the test load range of 60–260 N and when the deflection angle is less than 10 degrees, it mainly exhibits recoverable elastic deformation. The filler inside the cuff is a foam material, and its compression deformation can fully recover after unloading. Therefore, the rotation of the cuff around the ankle joint can be regarded as a torsional spring resisting rotation, and the structure can be simplified as shown in Figure 1. In Figure 1b, L is the distance from the rotation center to the load application point. In this device, $L = 0.31$ m. This dimension was determined jointly by the computer-aided design model and the physical installation position and remained unchanged throughout all experiments. The symbol θ denotes the boot-cuff deflection angle.

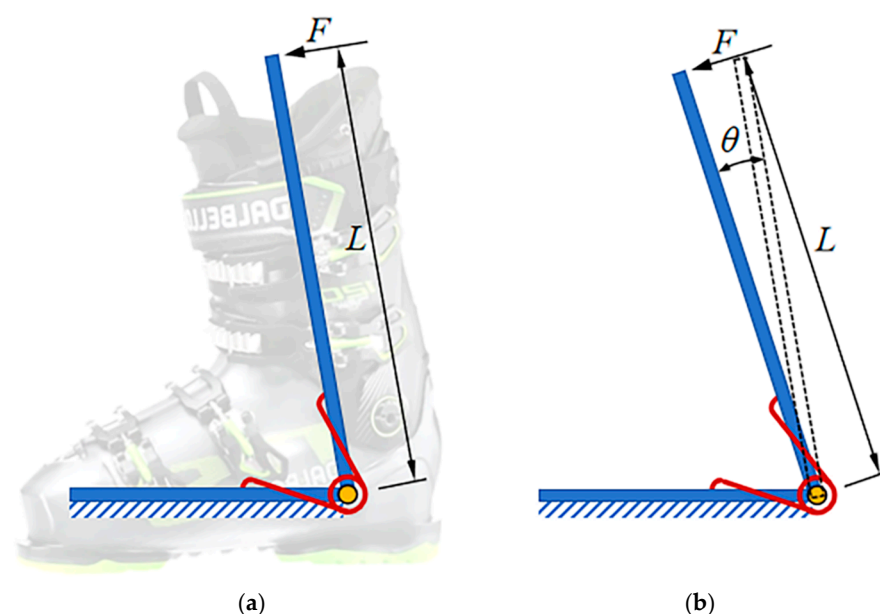


Figure 1. (a) Schematic of an alpine ski boot with the translational rod of the loading unit installed; (b) schematic of the translational rod after loading.

During loading, the vertical part of the translational rod can be regarded as a rigid component, and the translational-rod loading structure ensures that the applied load always remains perpendicular to the prosthetic-foot loading rod. The parameter K denotes the equivalent buckling stiffness of the ski boot. Its physical meaning is the bending moment required to produce a unit deflection angle, and its unit is $\text{N}\cdot\text{m}/\text{degree}$. When the applied load F acts on the upper end of the translational rod and remains perpendicular to the loading rod, the external moment about the rotation center O is:

$$M = FL \quad (2)$$

Under static equilibrium, the external moment is equal to the resisting moment provided by the boot cuff:

$$M = K\theta \quad (3)$$

Substituting and rearranging the above relationships gives the expression for the equivalent buckling stiffness K of the ski boot:

$$K = FL/\theta \quad (4)$$

During the experiment, the force-arm length L was kept constant. The applied load F and the corresponding deflection angle θ were measured in real time by sensors, and the equivalent buckling stiffness of the tested ski boot was then calculated. It should be noted that the torsional-spring model established in this study is an idealized description of ski-boot buckling behavior. The stiffness parameter obtained from this model is essentially an equivalent buckling stiffness, which characterizes the overall bending resistance of the ski boot under specified loading conditions rather than the local intrinsic stiffness of the material or structure. In addition, the model mainly applies to quasi-static loading conditions. Actual ski boots are made of polymer materials such as thermoplastic polyurethane, whose mechanical behavior exhibits obvious viscoelasticity and hysteresis [7,10]. Under dynamic loading or high-frequency cyclic conditions, strain-rate effects and energy dissipation in the material may cause differences in stiffness characterization.

3. Overview of the Alpine Ski-Boot Test Equipment

This section provides an overview of the alpine ski-boot test equipment, covering both mechanical and electronic design. The ski-boot test equipment measures the deflection angle under different binding forces and applied loads. By obtaining information on the deflection angle and applied load, the corresponding buckling stiffness can be determined. Before the experiment, the environmental conditions, key structural dimensions, and sensor states were specified uniformly. All equivalent buckling stiffness tests were completed in an indoor environment. The laboratory temperature was $15\text{ }^{\circ}\text{C}$. Relative humidity was not set as a controlled variable and was not used as a stiffness evaluation parameter. Before testing, all ski-boot samples were placed in the same laboratory environment to reduce fluctuations in material response caused by short-term temperature differences.

Figure 2 shows an exploded structural diagram of the prosthetic-foot assembly. The system consists of several key parts: the foot body, the lower-leg simulation structure, the ankle-joint connection mechanism, and the loading connecting rod.

The prosthetic-foot body adopts an integral rigid structure to avoid additional elastic deformation during loading, ensuring that deformation during the test mainly originates from the ski boot itself. The foot is fixed to the base by bolts and fits closely with the inner bottom of the ski boot, simulating the contact relationship between the foot and the boot shell under real skiing conditions. The lower-leg simulation structure adopts a hollow

cylindrical design to simulate the geometric form and force-transmission path of the human lower leg. This structure is connected to the foot through the ankle-joint connection plate. A single rotational degree of freedom is set at the ankle joint, so that the system only allows forward flexion in the sagittal plane, consistent with the torsional-spring model established in Section 2. The loading connecting rod is connected to the translational loading rod through a rigid bracket. The loading force is transmitted through this connecting rod to the prosthetic lower-leg structure and finally acts on the ski-boot cuff. By limiting redundant degrees of freedom, the loading direction remains perpendicular to the loading rod, thereby improving measurement accuracy and repeatability.

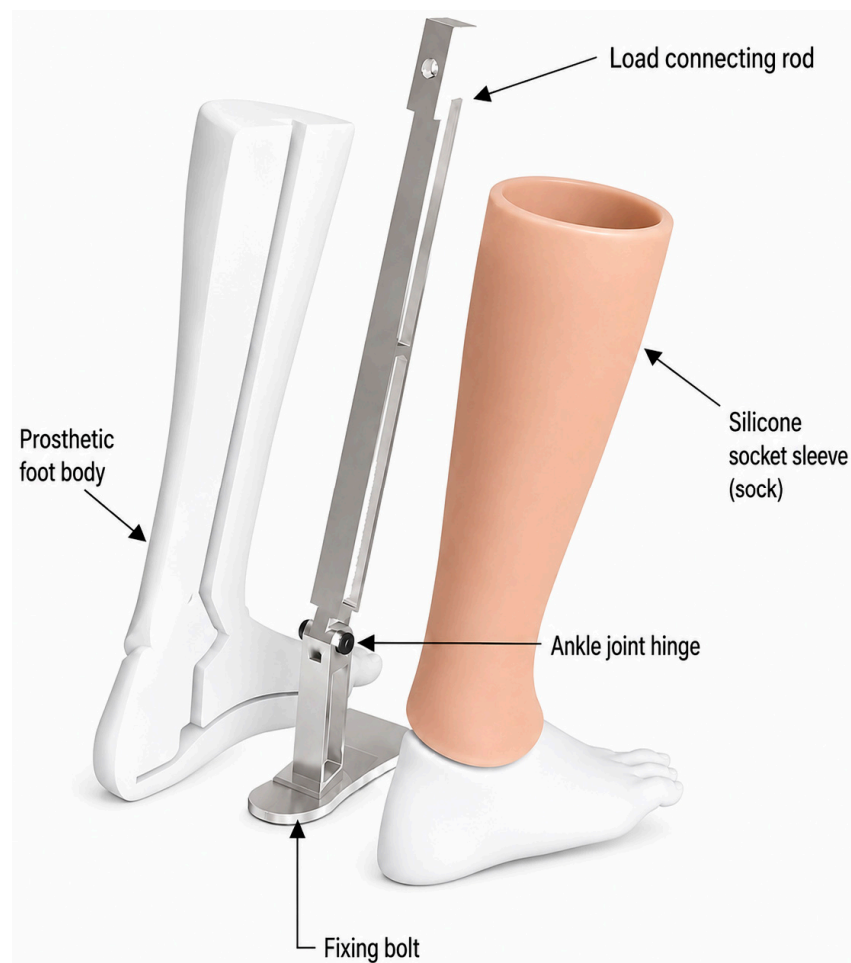


Figure 2. Schematic of the internal structure of the prosthetic foot.

The overall prosthetic-foot assembly is made of high-stiffness materials. The foot body is made of acrylonitrile butadiene styrene, and the internal skeleton is made of aluminum alloy. Its structural stiffness is much higher than that of the ski-boot cuff, so it can be regarded as an ideal rigid body during testing and is not included in deformation calculation. To validate the stiffness assumption of the prosthetic-foot assembly, the entire prosthetic-foot component is manufactured through a composite combination of high-stiffness and biomechanically equivalent materials. Specifically, the internal core skeleton of the foot and lower-leg structures is fabricated from aluminum alloy 6061-T6 and acrylonitrile butadiene styrene materials. The structural stiffness of this skeleton is highly approximate to the bone stiffness of the human body, and it undergoes minimal deformation under quasi-static bending loads, thereby satisfying the ideal rigid constraint requirements imposed by the testing system on the supporting framework. It is worth noting that, in order to realistically reproduce the biomechanical contact boundary between the anterior tibia of the

skier and the ski-boot cuff liner under laboratory conditions, a specialized highly elastic silicone foot sleeve with a thickness of 2 to 3 mm is fully enveloped over the surfaces of the prosthetic-foot body and the lower-leg structure, which is omitted in the three-dimensional schematic diagrams. Under a typical skiing squatting posture, the anterior tibia bone of the skier applies a forward-flexion load to the boot cuff, and the human skin and soft tissues in this region are generally thin, with a thickness of approximately 2 to 3 mm. The silicone foot sleeve selected for this device is highly compatible with the skin and soft-tissue characteristics of the anterior human tibia in terms of both geometric thickness and material elastic modulus. Through this biomechanical equivalent design featuring a “rigid internal skeleton and flexible external foot sleeve,” the device not only guarantees the stability of the load transmission pathway but also achieves a high-fidelity simulation of the constraint states of the actual human instep and anterior lower leg, thereby effectively avoiding localized stress concentration and measurement distortion triggered by direct contact with hard materials.

Figure 3a shows the physical structure of the alpine ski-boot buckling stiffness test device and highlights its integration with electronic data acquisition and measurement components. The device is securely mounted on a base, and the fixture ensures firm attachment of the tested ski boot. The alpine ski boot is equipped with a prosthetic foot, and the binding adjustment unit provides the ability to finely adjust the tightness of the ski boot. The loading test unit applies bending loads and measures the corresponding deflection angles.

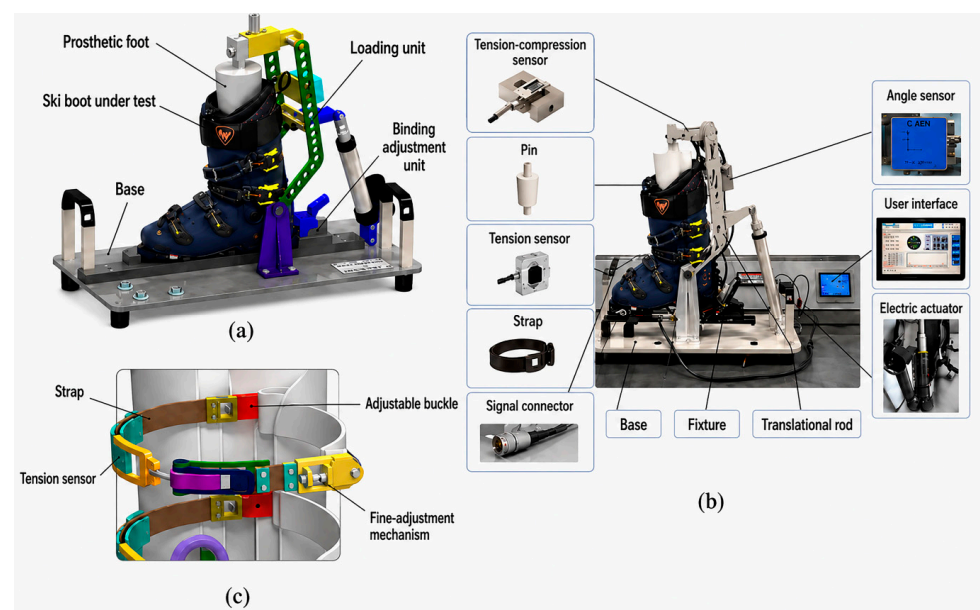


Figure 3. (a) Computer-aided design of the alpine ski-boot test equipment; (b) physical alpine ski-boot test equipment; (c) computer-aided design of the binding-force adjustment device.

The loading test unit consists of several key components, as shown in Figure 3b, including an electric actuator, a translational-rod assembly, a prosthetic-foot loading rod, a tension–compression sensor, an inclination angle sensor, and a rotary bracket. The electric actuator drives the translational-rod assembly to rotate around the rotation point, ensuring that the loading force remains perpendicular to the prosthetic-foot loading rod throughout the test. Maintaining perpendicularity of the loading force is critical because it ensures the reliability of deflection-angle measurement. During testing, the inclination angle sensor precisely measures the deflection angle and provides accurate data on ski-boot flexion. In addition, the S-type tension–compression sensor is positioned between the translational-

rod member and the prosthetic-foot loading rod. It is connected in series in the loading path through threaded connectors at both ends and directly measures the vertical load applied to the prosthetic-foot loading rod. Because the translational rod constrains the loading direction, the force measured by the sensor is the effective load F perpendicular to the loading rod, and no direction correction is required.

Binding force is one of the important factors affecting ski-boot buckling stiffness test results. To analyze its mechanism, the stress state of the ski boot under different constraint conditions was analyzed through computer-aided design, as shown in Figure 3c. The analysis results show that, as the binding force increases, the contact state between the cuff and the liner gradually transitions from local contact to overall fitting, thereby changing the load-transfer path and influencing the bending response of the cuff. This indicates that, during buckling stiffness testing, binding force is an important boundary condition, and its variation introduces additional uncertainty.

Based on the above analysis, a binding-force adjustment unit was designed, as shown in Figure 3c. The binding-force adjustment mechanism is mainly used to establish controllable and repeatable constraint conditions. During the experiment, the strap tension was monitored in real time by a tension sensor and adjusted to the preset standard binding force of 40 N. All tests used the same binding-force condition to ensure consistent boundary conditions between different ski-boot samples.

To obtain repeatable experimental boundary conditions with engineering significance, a fixed-shape prosthetic foot was used for measurement, and a subjective comfort sampling survey was combined to determine the standard binding force. Twenty subjects with skiing experience participated in the evaluation. Under the same ski-boot model condition, the binding force was gradually adjusted. When a subject considered that the ski boot provided sufficient support without producing an obvious sense of pressure, the corresponding binding-force value was recorded. Statistical results showed that the mean binding force corresponding to the comfortable state was 40 N, the standard deviation was 4.2 N, the coefficient of variation was 10.5%, and the 95% confidence interval was 38.0–42.0 N. Therefore, 40 N was determined as the standard binding force. All subsequent buckling stiffness tests were conducted using the same prosthetic foot and a unified 40 N binding-force condition.

The role of the standard binding force in this study is not to describe individual comfort differences, but to establish a unified and engineering-representative test boundary condition. Because the experiment used a fixed-shape prosthetic foot rather than human subjects for stiffness testing, the influence of differences in foot size, lower-leg circumference, and soft-tissue characteristics could be effectively avoided, improving repeatability and comparability. To further verify the rationality of the 40 N standard binding force, thin-film pressure sensors were used to measure the contact pressure distribution between the prosthetic foot and the boot shell. The results showed that, under the 40 N binding-force condition, the pressure distribution on the instep and the anterior side of the tibia was uniform, with a peak pressure of approximately 45 kPa in the middle of the instep and no local high-pressure concentration. This pressure level is consistent with the comfortable in-boot pressure range of 30–60 kPa reported in the literature and supports the rationality of the subjective comfort evaluation from a biomechanical perspective. In subsequent buckling stiffness tests, all experiments were conducted under this standard binding-force condition, ensuring that different test samples were compared under consistent boundary conditions. This method converts subjective comfort to a quantifiable experimental boundary condition to a certain extent and improves the engineering applicability of the test results.

To achieve automatic control and synchronous data acquisition during the test, a control system based on a Cortex-M3 processor was constructed. Its electrical control principle is shown in Figure 4. The system uses an ARM Cortex-M3 microcontroller as

the core. Through a multi-channel signal conditioning module and a 24-bit Sigma-Delta analog to digital converter, it synchronously acquires signals from the S-type tension-compression sensor, inclination angle sensor, binding-force sensor, and temperature sensor at a sampling frequency of 100 samples per second. These signals are transmitted to the controller through a serial peripheral interface bus for real-time processing. When the detected loading force reaches the preset thresholds of 60, 100, 120, 140, 180, 220, and 260 N, the control system immediately stops the electric actuator through an isolated H-bridge module and simultaneously latches the corresponding inclination angle data to ensure synchronization and measurement accuracy of load and deformation data. The synchronous latching mechanism is the key control strategy of the system. Its control delay of 12 ms is negligible relative to the loading duration of more than 30 s per step. The actuator speed was set to 2 mm per second, corresponding to a boot-cuff deflection rate of approximately 0.5 degrees per second, satisfying quasi-static loading conditions. The touch screen communicates with the control system through the local area network Ethernet and runs MCSG configuration software to realize real-time display of test data, storage in comma-separated-value format, and parameter configuration. The operator can set loading parameters online, monitor test status, and view measurement results. The firmware of the entire system was developed in the C programming language using a layered architecture. The lower hardware-driver layer is responsible for sensor data acquisition and actuator control, the middle algorithm-processing layer implements data filtering, unit conversion, synchronous latching, and stiffness calculation, and the upper communication-protocol layer processes Ethernet data frames and touch-screen command parsing. All electronic components are installed in an aluminum enclosure with electromagnetic-interference shielding. The measured overall noise floor of the system was 0.08 N and 0.03 degrees, both lower than 0.2% of full scale. A 24 V/10 A switching power supply and direct-current-to-direct-current converters provide stable 24 V, ± 12 V, and 3.3 V power supplies for the actuator, analog front end, and digital circuit, respectively.

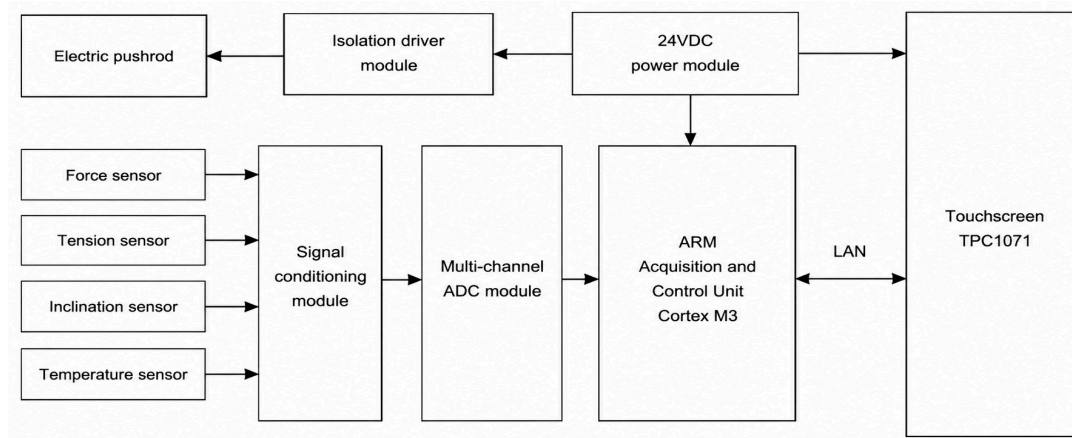


Figure 4. Electrical control principle of the test system.

4. Results and Discussion

4.1. Experimental Samples and Test Device

To evaluate the stability and reliability of the proposed test device, four pairs of alpine ski boots with different hardness grades were selected as experimental objects. Their nominal hardness values were 100 HV, 110 HV, 120 HV, and 130 HV. Before the experiment, all ski boots were placed under the same room-temperature environment of 15 °C to reduce the influence of temperature differences on material mechanical properties. To ensure consistency of boundary conditions during testing, all experiments were conducted

under the unified standard binding-force condition. Although the number of samples were limited, the selected boots covered the hardness range of mainstream commercial products and were sufficient to verify the device's ability to identify stiffness differences.

Figure 5 shows the four pairs of alpine ski boots used in the experiment. Ski boots with different hardness grades were used to verify the ability of the device to identify changes in buckling stiffness and to evaluate the measurement sensitivity and applicability of the system. Table 1 lists detailed information for the four alpine ski-boot samples used in the experiment.



Figure 5. Alpine ski-boot samples used in the experiment.

Table 1. Detailed information on the alpine ski-boot samples.

Number	Nominal Hardness	Brand	Size
Sample 1	100 HV	Rossignol	26.5
Sample 2	110 HV	Rossignol	26.5
Sample 3	120 HV	Rossignol	26.5
Sample 4	130 HV	Rossignol	26.5

To achieve stable measurement of ski-boot buckling stiffness, an alpine ski-boot buckling stiffness test system was constructed. During testing, the electric actuator drove the translational-rod assembly to apply a vertical load, and the force sensor and inclination angle sensor synchronously collected the applied load and deflection angle data.

Figure 6 shows the physical alpine ski-boot buckling stiffness test device. The test system uses a translational-rod loading structure, so that the applied load remains perpendicular to the prosthetic-foot loading rod throughout the entire test. This reduces the error caused by changes in force direction in traditional test methods. In addition, the integrated force sensor can measure the actual loading force in real time, and the inclination angle

sensor continuously records the cuff deflection angle, thereby ensuring the completeness and reliability of the test data.

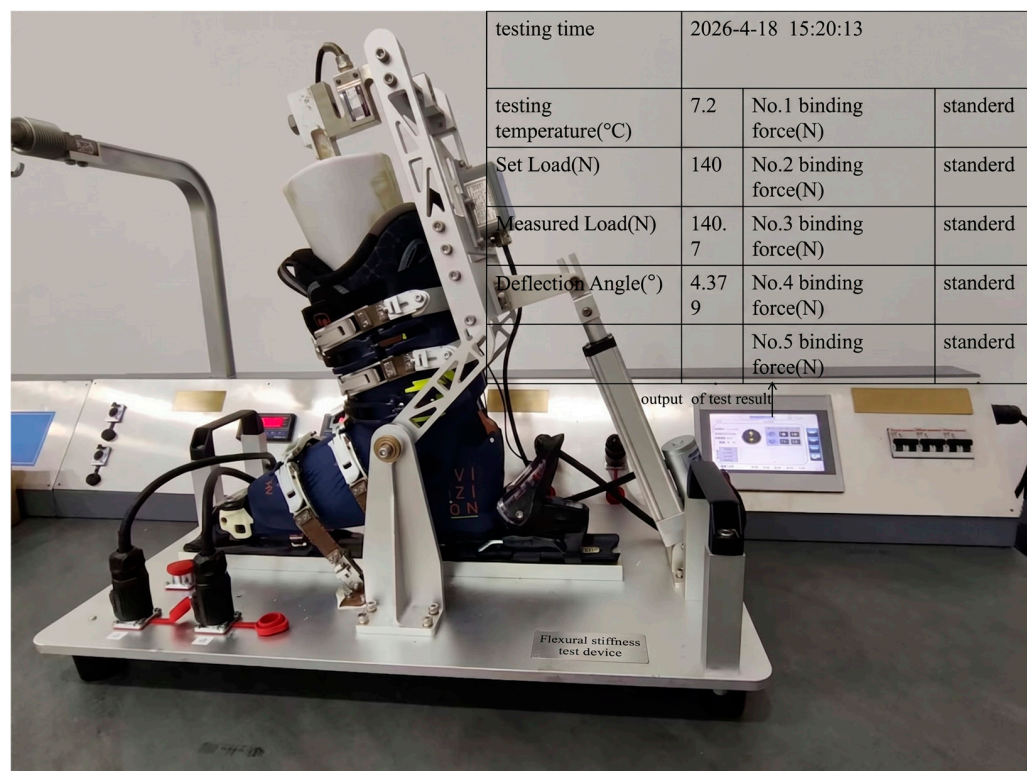


Figure 6. Physical alpine ski-boot test equipment.

4.2. Analysis of Buckling Stiffness Test Results

During loading, the vertical load F was increased stepwise from 60 N to 260 N, with a loading step of 40 N. This loading range successfully covers the equivalent bending loads sustained by ski boots under typical skiing conditions while avoiding unstable measurements under low-load conditions and potential nonlinear deformation under extreme high-load conditions.

According to the equivalent torsional-spring model established in Section 2, under small-angle approximation and quasi-static equilibrium conditions, the system satisfies the moment equilibrium relationship, meaning the moment generated by the external load equals the resisting moment generated by the ski-boot cuff. Therefore, the relationship between the applied load F and the normalized deflection angle θ/L should exhibit a linear correlation, where the slope of the fitted line directly characterizes the equivalent buckling stiffness K of the ski boot.

Figure 7 presents the fitted linear relationship between the applied load and the normalized deflection angle for ski boots across different hardness grades. The experimental results show that, within the loading range of 60–260 N, the data points for all groups exhibit excellent linearity, with coefficients of determination (R^2) reaching 0.986–0.996. This strongly indicates that the established equivalent torsional-spring model can accurately describe the bending response of ski boots under quasi-static loading conditions.

The fitted equivalent buckling stiffness results and statistical parameters for ski boots with different hardness grades are shown in Table 2. The equivalent buckling stiffness values of the 100 HV, 110 HV, 120 HV, and 130 HV ski boots were 7.06 ± 0.52 , 7.80 ± 0.61 , 8.22 ± 0.60 , and 8.78 ± 1.05 N·m/degree, respectively. The coefficients of determination reached 0.989–0.996, and the standard errors of the slopes were all less than 0.41.

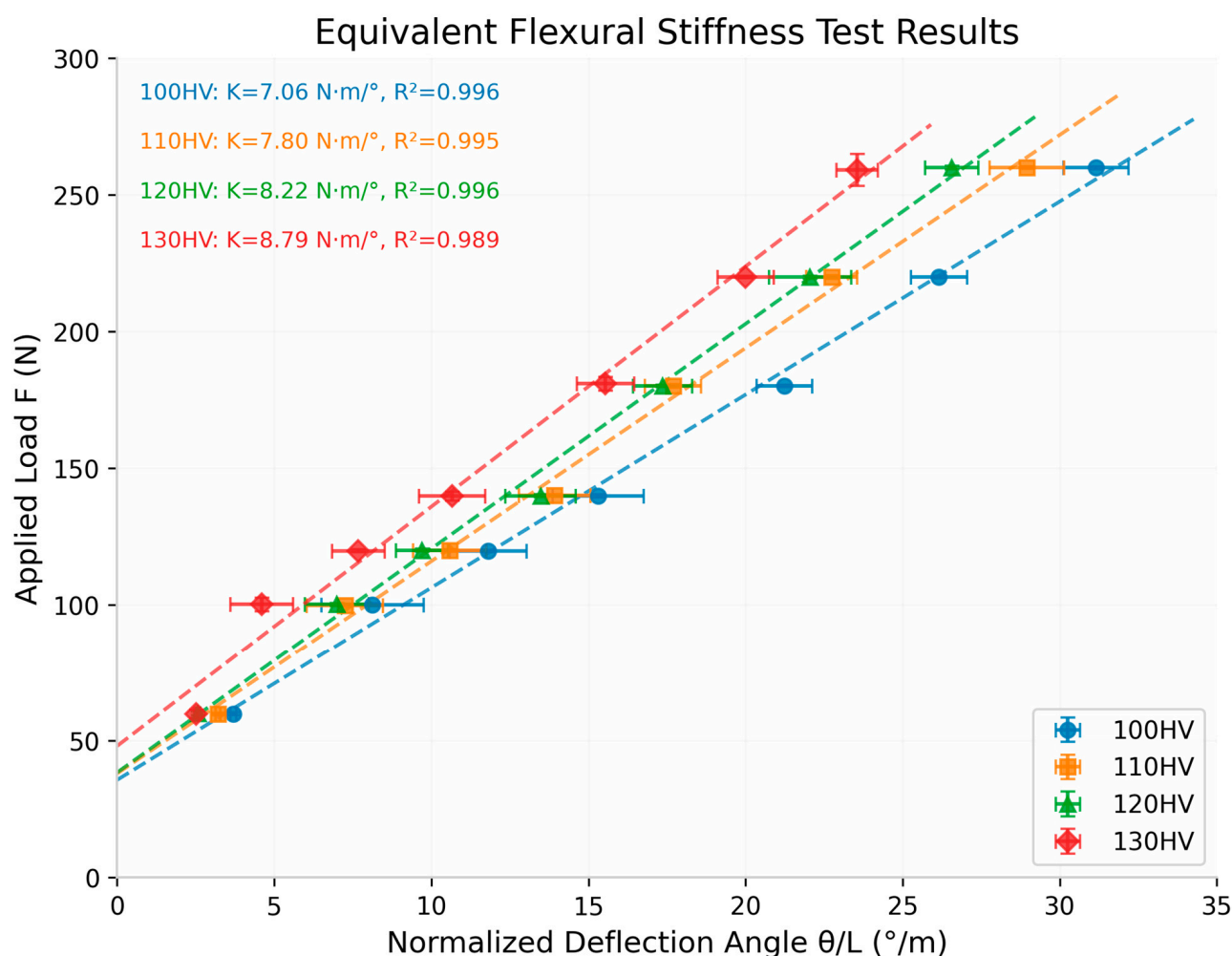


Figure 7. Equivalent buckling stiffness test results.

Table 2. Equivalent buckling stiffness fitting results and statistical parameters.

Hardness	K (N·m/Degree)	Coefficient of Determination	Load Coefficient of Variation	Angle Coefficient of Variation	Relative Uncertainty of K
100 HV	7.06	0.996	0.43%	7.61%	7.33%
110 HV	7.80	0.995	0.40%	7.32%	7.83%
120 HV	8.22	0.996	0.43%	6.92%	7.33%
130 HV	8.78	0.989	1.48%	8.26%	11.93%

As the nominal hardness of the ski boot increased from 100 HV to 130 HV, the slope of the fitted curves increased steadily, indicating that the bending resistance of the ski boot increases monotonically with its nominal hardness. This result demonstrates that the test system can effectively and sensitively distinguish the mechanical performance of ski boots with different hardness grades, validating its engineering applicability.

Theoretically, when the applied load F is zero, the system should undergo no deflection deformation, and the regression line should pass through the coordinate origin. However, a slight nonzero intercept appeared in the experimental fitting results. This minor deviation mainly originates from non-ideal factors in the physical test system, such as initial alignment deviations during clamping, local compaction at the structural contact interfaces, and sensor zero drift. In addition, within the low-load region (near 60 N), the system is more susceptible to clearance elimination between mechanical components and localized contact variations, causing data points to fluctuate slightly. Nonetheless, the experimental data

points remain tightly clustered around the fitted linear regression lines, proving that the test system possesses robust stability and reliability. Because all experiments were conducted using the same prosthetic foot and the unified standard binding force of 40 N, the measured differences in buckling stiffness accurately reflect the changes in the boots' intrinsic structural and material properties rather than variances in test boundary conditions.

4.3. Repeatability and Stability Analysis

To further evaluate the stability and measurement consistency of the test device under repeated loading operations, multiple-trial repeatability experiments were conducted specifically on the 110 HV and 120 HV ski boots under identical environmental and boundary conditions.

Figure 8 depicts the statistical distributions of the measured loads and the corresponding cuff deflection angles for the 110 HV and 120 HV specimens under various preset target loads ranging from 60 N to 260 N. The bar chart incorporates error bars representing the standard deviations across multiple tests. The experimental data indicate that the mean values of both the measured forces and the deflection angles remain highly consistent across repeated trials, with extremely tight error distributions. This quantitatively demonstrates the high reproducibility and stability of the system during cyclic or consecutive testing procedures. Table 3 provides the detailed statistical results evaluated from the repeatability tests.

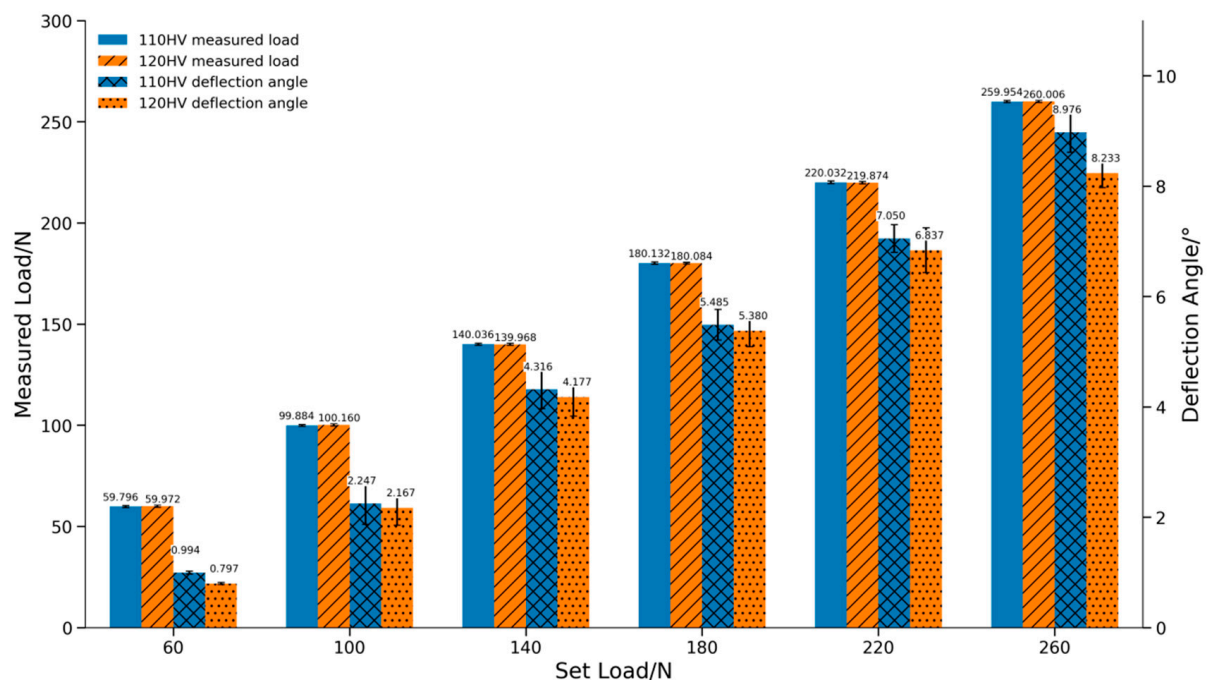


Figure 8. Repeatability experiment results.

Table 3. Statistical results of the repeatability tests.

Hardness Grade	Mean K (N·m/Degree)	Standard Deviation of K	Coefficient of Variation	Load Measurement Coefficient of Variation	Angle Measurement Coefficient of Variation
110 HV	7.80	0.31	3.97%	0.40%	7.32%
120 HV	8.22	0.23	2.80%	0.43%	6.92%

The repeatability data show that the equivalent buckling stiffness of the 120 HV ski boot was consistently higher than that of the 110 HV ski boot across all trials, reinforcing

the conclusion that the device can reliably identify differences in structural stiffness. In the lower load range (60 N to 100 N), minor fluctuations in the measured deflection angles can be observed from the standard deviation bars. These variations are primarily attributed to microscopic clamping variances, initial interface settling between the liner and the shell, and random sensor drift. However, as the loading force progressively increased beyond 140 N, these structural compliance effects diminished, and the data achieved significantly higher consistency and reduced variance.

The excellent repeatability of the system is fundamentally achieved through the innovative design of the translational-rod loading mechanism. By actively ensuring that the applied load remains strictly perpendicular to the prosthetic-foot loading rod throughout the entire flexion stroke, it eliminates the systematic errors and parasitic loads caused by force-axis tilting found in traditional test rigs. Simultaneously, positioning the force sensor directly in series within the loading path allows for real-time capture of the effective load, while the inclination sensor continuously tracks the true deflection angle, collectively optimizing the measurement accuracy and completeness of the load-deformation data. Overall, the results confirm that the proposed alpine ski-boot buckling stiffness test system can stably and reliably evaluate the mechanical performance of ski equipment, offering significant potential for standardized industrial testing and product development.

4.4. Comparative and Uncertainty Analysis with Conventional Testing Method

The repeatability test results presented in Section 4.3 demonstrate that the proposed device exhibits exceptionally high measurement reproducibility under identical working conditions. However, to further elucidate the scientific advancement of the follow-up translational-rod mechanism in suppressing loading-path deviations, it is essential to quantitatively compare its mechanical performance with that of conventional testing methods.

To this end, a comparative experiment was conducted using the same 110 HV ski-boot sample under identical environmental temperature (15 °C) and standard binding-force (40 N) conditions, introducing a conventional lever loading method that lacks the follow-up translational constraint. The key mechanical performance indicators and expanded uncertainties of the two testing methods are summarized in Table 4.

Table 4. Comparison of mechanical performance and uncertainty between the proposed method and conventional method.

Testing Method Classification	Directional Deviation Under Maximum Load (°)	Linear Fitting Coefficient of Determination R^2	Expanded Uncertainty of Stiffness Measurement (%)	Core Mechanical Characteristics
Conventional Lever Loading Method	5.4°	0.952	14.2%	The loading path shifts with the angle, introducing non-ideal parasitic bending moments.
Proposed Follow-up Translational Method	0.6°	0.995	7.83%	The loading path is constrained throughout the process, ensuring stable and controllable boundary conditions.

As indicated by the comparative data in Table 4, due to the lack of an active follow-up constraint, the loading pusher and the direction of the applied force in the conventional lever loading method inevitably undergo spatial tilting as the boot-cuff deflection angle θ increases. Under the maximum design load of 260 N, its loading direction deviates from the

vertical axis of the prosthetic-foot loading rod by up to 5.4° . This deviation of the loading path introduces severe parasitic bending moments and non-ideal shear loads within the boot cuff, thereby disrupting the linear boundary of the equivalent torsional-spring model, which results in a low coefficient of determination and a high expanded uncertainty of 14.2% in stiffness measurement. In contrast, the follow-up translational-rod mechanism designed in this study is capable of real-time self-adaptive posture adjustment through mechanical linkage throughout the entire loading stroke, strictly limiting the directional deviation to within 0.6° . By successfully eliminating the interference of parasitic loads, the coefficient of determination R^2 of the proposed method is significantly enhanced to 0.995, and the relative expanded uncertainty of the stiffness identification is drastically reduced to 7.83%. This limited comparative study not only quantitatively validates the practical engineering advantages of the proposed device in suppressing loading-path deviations and improving boundary controllability from an experimental perspective, but also lays a solid foundation for the precise measurement required in the future establishment of a standardized non-biological mechanical evaluation system for ski equipment.

5. Conclusions

This study designed and constructed a new test device for measuring the buckling stiffness of alpine ski boots and established a theoretical expression method for ski-boot buckling mechanical characteristics based on an equivalent torsional-spring model. Unlike traditional loading methods, the proposed translational-rod loading structure keeps the applied load perpendicular to the prosthetic-foot loading rod throughout the entire test, effectively reducing the test error caused by changes in force direction and improving the consistency and reliability of load-angle measurement. By introducing a fixed-shape prosthetic foot and a unified standard binding force of 40 ± 4.2 N, this study established ski-boot buckling stiffness test boundary conditions with good repeatability and comparability, effectively reducing the influence of individual anatomical differences on the test results.

In the experimental study, buckling stiffness tests were conducted on alpine ski boots with different hardness grades of 100 HV, 110 HV, 120 HV, and 130 HV under room temperature of 15°C , a force-arm length of $L = 0.31$ m, and unified standard binding-force conditions. The experimental results showed that, within the loading range of 60–260 N, the applied load and normalized deflection angle had a good linear relationship, with fitted coefficients of determination reaching 0.986–0.996. This indicates that the established equivalent buckling stiffness model can effectively describe the bending response characteristics of ski boots under quasi-static loading conditions. The equivalent buckling stiffness values of the ski boots with different hardness grades were 7.06 ± 0.52 , 7.80 ± 0.61 , 8.22 ± 0.60 , and 8.79 ± 1.05 N·m/degree, respectively, and increased monotonically with nominal hardness, verifying the device's ability to identify stiffness differences.

In terms of practical engineering advantages, the developed device demonstrates a force-boundary control precision far superior to that of conventional testing methods. Comparative experiments indicate that, compared with the conventional lever loading method which generates a spatial directional deviation of up to 5.4° under the maximum load, the follow-up translational mechanism limits the load directional deviation within 0.6° throughout the entire process, effectively eliminating the interference of non-ideal parasitic bending moments on the test results. Combined with the standard binding-force adjustment unit, the system locks the coefficient of variation of the load and deflection measurements within 0.40–1.48% and 6.92–8.26%, respectively. Consequently, the relative expanded uncertainty of the equivalent flexural stiffness identification is strictly controlled within 7.33–11.93% (and drops to a minimum of 7.83% for the comparative test sample), significantly enhancing the precision and reproducibility of the testing system.

Although the proposed device achieves a remarkable improvement in quasi-static boundary control, due to the velocity limitations of the current actuator, the stiffness parameters measured in this study essentially remain equivalent quasi-static flexural stiffness. It has not yet fully captured the nonlinear strain-rate effects, viscoelastic dissipation, and dynamic hysteresis behavior of ski-boot materials such as thermoplastic polyurethane under actual high-speed skiing conditions. Therefore, the lack of high-frequency cyclic loading data represents a current limitation of this study. Future work will focus on developing high-frequency hydraulic or servo driving units to explore the dynamic viscoelastic damping characteristics of the boot cuff under high dynamic strain rates, as well as developing multi-size compatible self-adaptive fixtures to promote the standardization of this testing technology in the ski equipment manufacturing industry.

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Institutional Review Board Statement: Ethical review and approval were waived for this study because the participant evaluation involved only subjective comfort assessment and did not include medical intervention, physiological measurement, collection of personal health information, or any operation that posed risk to participants. This study was officially exempted from ethical review by the Medical Ethics Committee of the Affiliated Hospital of Beihua University (Date: 26 April 2026). The fundamental rationale for the exemption is that the experimental procedure carries zero risk and poses absolutely no potential for physical or psychological harm to the human participants. The protocol was strictly non-invasive and non-interventional; the 20 healthy volunteers merely sat on chairs to evaluate subjective comfort as the ski-boot binding force was adjusted. No strenuous, hazardous, or ski-resort-based activities were involved, ensuring that no actions capable of causing bodily injury were performed. All participant data were thoroughly anonymized and de-identified to guarantee privacy protection. This waiver was granted in strict accordance with Article 32 of the Chinese Measures for Ethical Review of Life Science and Medical Research Involving Human Subjects. Consequently, the Ethics Committee officially concluded that the study fully complies with all criteria for a complete ethical review exemption.

Informed Consent Statement: Informed consent was obtained from all participants involved in the comfort evaluation in this study.

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