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# What static and dynamic properties should slalom skis possess? Judgements by advanced and expert skiers

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**Abstract**

Flexural and torsional rigidity are important properties of skis. However, the flexural and torsional rigidity that lead to optimal performance remain to be established. In the present study, four pairs of slalom skis that differed in flexural and torsional rigidity were tested by advanced and expert skiers. Using a 10-item questionnaire, different aspects of the skis' performance were rated on a 9-point scale. For each pair of skis, physical measurements were compared with the ratings of the two groups of skiers. Correlations (Spearman) were then determined between (i) different mechanical properties of the skis (static and dynamic), (ii) subjective assessments of the participants, and (iii) properties of the skis and the participants' assessments. The latter showed that expert skiers rate the aspects of the skis more accurately than advanced skiers. Most importantly, expert skiers are particularly sensitive to torsion of the skis. These results suggest that such highly rated elements should be addressed in future ski designs.

**Keywords:** *Slalom skis, subjective judgement, mechanical properties, vibration and damping*

## Introduction

As in most sports, high-level skiing requires a combination of precision equipment and highly trained motor and perceptual skills if the athlete is to perform successfully. In this context, the quantification of "feel" in any domain of sport is a complex topic combining the athlete's perception with static and dynamic information transferred by the sports equipment. Few studies have tried to define and quantify "feel" in connection with sports, most of which examined golf or tennis (Cross, 1998; Roberts, Jones, & Rothberg, 2001). Also, few studies have focused on the perception of different ski properties by skiers (Federolf, Auer, Fauve, Lüthi, & Rhyner, 2006; Lüthi, Federolf, Fauve, & Rhyner, 2006; Nachbauer, Rainer, & Schindelwig, 2004), or suggested a method to develop more customer-specific skis (Darques, Carreira, de la Mettrie, & Bruyant, 2004).

The dynamic properties of skis were first investigated systematically by Piziali and Mote (1972). Glenne, Jorgensen, and Chalupnik (1994) subsequently compared different measurement devices, showing that small amplitude tests such as the ISO test may not be representative of field conditions. More recently, various groups have integrated the boot/binding system into their analyses so as to reproduce real skiing conditions more accurately (Casey, 2001; Glenne, DeRocco, & Foss, 1999). Comparisons with results obtained from free- suspension tests demonstrate the important role of the boot and binding in cutting off high frequencies. The behaviour of skis on snow has also been studied *in situ* using accelerometers (Nemec, Kugovnik, & Supej, 2001), leading to the conclusion that carving skis result in less vibration during turns by preventing skidding.

In a recent study, the influence of skis' constituent materials on their overall dynamic behaviour was investigated, and the importance of the influence of the viscoelastic components on the skis' damping behaviour was demonstrated (Fischer *et al.*, 2006). In this context, it is generally accepted that

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resonance is often detrimental to performance in that it reduces ground contact, and the skier is no longer able to continue the carved turn. High-amplitude deformations at low frequencies are of particular concern in this respect.

The purpose of this study was to examine the influence of the skis' mechanical properties on the "feel" and the perceived performance of the skier. To this end, we used four pairs of slalom skis, characterized them in the laboratory regarding their static and dynamic properties, and had them rated in the field by advanced and expert skiers. Correlations were then determined between the measured ski properties to ensure that the latter were coherent. Moreover, correlations between the subjective evaluations of the participants were determined to investigate possible links between important factors in skiing. Finally, we correlated the subjective evaluations with the skis' mechanical properties.

## Materials and methods

We selected a range of constituent materials and used them in different proportions to produce four different pairs of skis with specifically tailored differences in their mechanical properties. We then asked advanced and expert skiers to judge these skis to determine which static and dynamic properties are important for skiers to "feel" that a ski has been optimized.

### *Measurement of static and dynamic properties of skis*

Four pairs of slalom skis (length 156 cm, radius 11 m), each consisting of a sandwich structure comprising a range of materials, were constructed such that their mechanical properties (i.e. their flexural and torsional rigidity) differed significantly. The specific aim was to produce skis with different combinations of flexural versus torsional rigidity – that is, hard/hard, hard/soft, soft/hard, and soft/soft (denoted as H/H, H/S, S/H, and S/S, respectively). All the skis were identical in geometry and design, and any differences in weight were not perceivable by the participants. The same bindings, allowing for an easy boot size change, were mounted on all the skis.

The constituent materials' thickness and width varied continuously along the skis. It was therefore difficult to estimate an effective modulus for these sandwich structures without using numerical methods. An approach that is currently widely employed for skis and snowboards makes use of *overall-* or *specimen properties* (Lüthi *et al.*, 2006; Nachbauer *et al.*, 2004). The "specimen flexural rigidity", $K$, was measured using a three-point configuration, and was defined as the load $F$ applied at the position of the centre of the ski boot divided by the deflection, $d$, at the same position:

$$K = \frac{F}{d} \tag{1}$$

The "specimen torsional rigidity", $T$, was determined by clamping the binding onto a rigid ski boot replacement and applying a torque $M$ to either the rear ($T_t$) or the front part ($T_f$) of the ski. $T_t$ and $T_f$ were then obtained by dividing $M$ by the resulting torsional angle $\alpha$, and then multiplying by the distance $l$ between the position of the clamp and the position where the torque was applied:

$$T = \frac{M}{\alpha} l \tag{2}$$

Figure 1 shows $K$, $T_f$, and $T_t$ for the four different ski-binding systems used in this study (S/S, S/H, H/S, and H/H). Under flexural loading, $K$ of the stiffest ski exceeded that of the most compliant skis by 18% (Figure 1a), while $T_f$ for the stiffest skis was 61% higher than for the most compliant skis (Figure 1b). The different combinations of flexural and torsional rigidity of the skis are shown in Figure 2, in which $T$ (average of $T_f$ and $T_t$) is plotted against $K$.

Measurement of the ski-binding system's dynamic behaviour was conducted as follows. Each system was fixed to the equipment by a phantom shoe placed in the binding and pressed on the other side by a 20-cm long aluminium plate centred at the position of the ski boot centre with a pressure of 3.5 bar. A small hammer hit the front part of the ski providing a standardized shock. To induce both torsional and flexural modes, the hammer was placed so as to hit the ski close to its edge and away from the clamp. The vibration was measured with two accelerometers taped onto the ski base. Figure 3a shows a typical frequency spectrum for the front part of a ski. The first, second, and fourth peaks correspond to flexural modes, while the third and fifth peaks correspond to torsional modes. For each peak, the corresponding decay in amplitude was measured and fitted with an exponential (Figure 3b), and the damping for each mode was defined in terms of the logarithmic decrement, $\lambda$.

The aforementioned measurements were carried out in a cold chamber at $-10^\circ$C, which corresponded to the average temperature during the field tests. Each ski-binding system was measured five times and mean values were used in the analyses.

The damping behaviour of the four different skis is summarized in Table I for the three first modes. $\lambda_1$ corresponds to damping at the first resonance

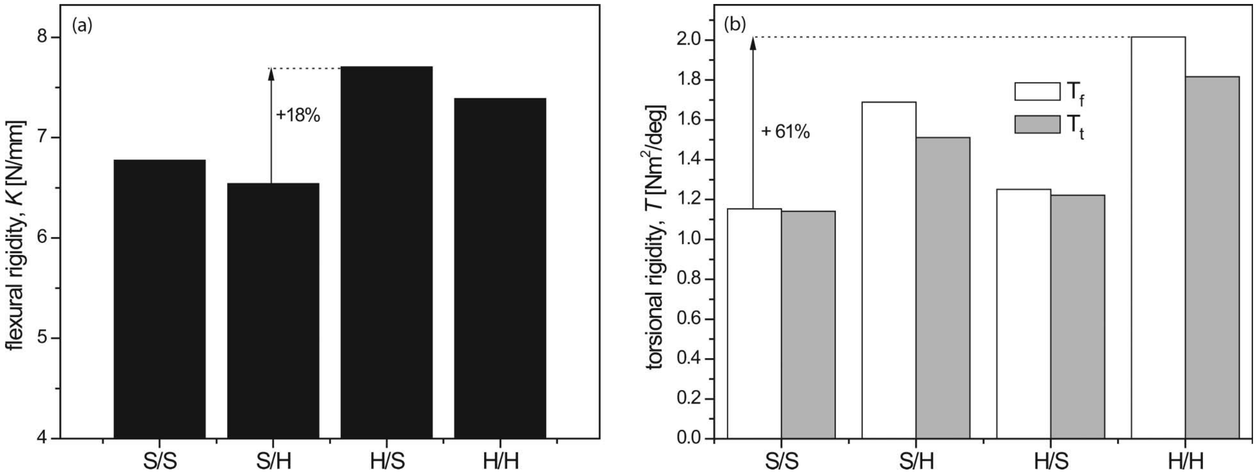

Figure 1. Results for (a) $K$ and (b) $T_f$ and $T_t$ for the different ski-binding systems, indicating the maximum differences between the most rigid and the most compliant system, respectively. Combinations of flexural/torsional rigidity: HH = hard/hard, HS = hard/soft, SH = soft/hard, SS = soft/soft.

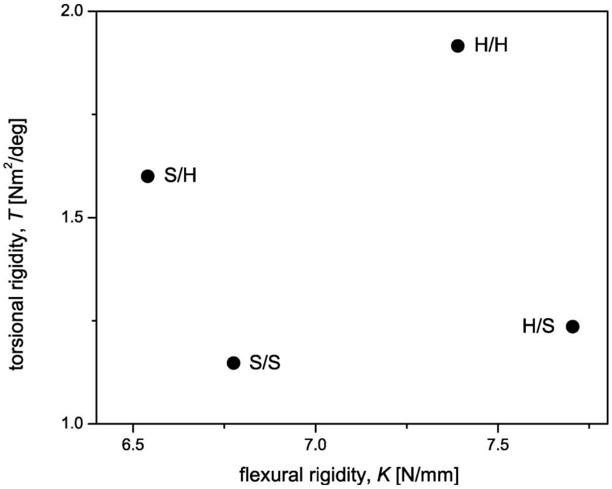

Figure 2. $T$ vs. $K$ for the four ski-binding systems used in this study. Combinations of flexural/torsional rigidity: HH = hard/hard, HS = hard/soft, SH = soft/hard, SS = soft/soft.

frequency, $f_1$, $\lambda_2$ to damping at the second resonance frequency, $f_2$, and $\lambda_3$ to damping at the third resonance frequency, $f_3$.

### *Assessment of perceived characteristics of skis*

*Participants.* Five expert male skiers aged 27 – 35 years (mean height 1.85 m, $s = 0.03$; body mass 81.2 kg, $s = 2.8$), and five advanced male skiers aged 24 – 38 years (height 1.80 m, $s = 0.04$; body mass 76.2 kg, $s = 4.2$) volunteered to participate in the study. The expert skiers were all professional ski instructors, used to ski racing. The advanced skiers were regular skiers with no particular ski racing experience. The study was carried out in Davos, Switzerland.

*Questionnaire.* The essential criteria with which to rate a good slalom ski were established from (i) a survey among experienced skiers and (ii) ski magazines with many years experience of ski testing. For carved turns, the most cited criteria plus those corresponding to basic ski characteristics (ease in initiating the turn, accuracy, self-steering, skidding, tracking stability, energy restitution, forgiveness, quietness at high speed, bending stiffness, torsional stiffness), as well as a more general question (overall impression), were used in the questionnaire. In the case of short, skidded turns, some of these factors turned out to be irrelevant (self-steering, tracking stability, energy restitution, forgiveness, quietness at high speed, bending stiffness, torsional stiffness), while others appeared to be important (grip and quietness). Thus, for carved turns we used a 10-item questionnaire but a 5-item questionnaire for the short, skidded turns, based on the criteria mentioned above. In both cases, the questionnaire consisted of a 9-point scale for each criterion (1 = very bad, 9 = excellent; or as indicated on the questionnaire). The questionnaires for the carving and short, skidded turns tests are presented in Figure 4a and 4b, respectively.

To ensure that all participants had a similar understanding of the different factors described in the questionnaire, each criterion was explained in more detail as follows:

- *Ease in initiating the turn*: facility with which the turn is initiated.
- *Accuracy*: ability of the ski to take the desired direction accurately after initiation of the turn.
- *Self-steering*: ability of the ski to turn without high energy expenditure.

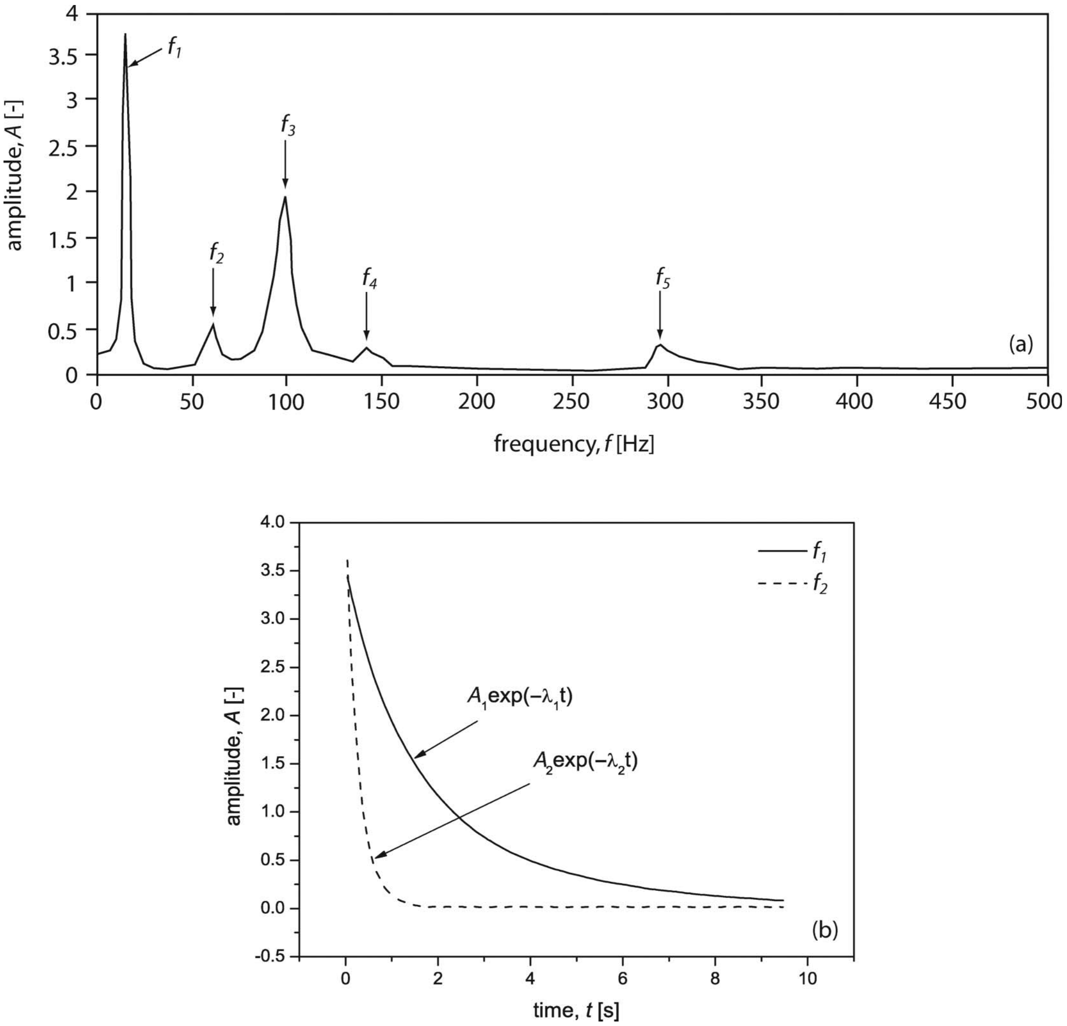

Figure 3. Typical damping measurement showing (a) a frequency spectrum and (b) a plot of amplitude versus time used to determine the logarithmic decrement, $\lambda$, of the corresponding resonance frequencies.

Table I. Damping coefficients of the first, second, and third resonance frequencies for the four skis used in this study.

| | S/S | S/H | H/S | H/H |
|---|---|---|---|---|
| $\lambda_1$ | 0.71 | 0.69 | 0.77 | 0.76 |
| $\lambda_2$ | 3.72 | 5.03 | 4.17 | 3.84 |
| $\lambda_3$ | 6.98 | 6.93 | 6.98 | 6.87 |

- *Tracking stability*: ability of the ski to follow the trace as on rails.
- *Energy restitution*: ability of the ski to restitute the stored elastic energy at the end of the turn (acceleration).
- *Forgiveness*: ability of the ski to forgive technical inaccuracies.
- *Quietness at high speed*: ability of the ski to absorb shocks at high speed (damping of the ski).
- *Grip*: ability of the ski to limit skidding during the short, skidded turn.
- *Quietness*: ability of the ski to absorb shocks during short, skidded turns at low speed (damping of the ski).
- *Bending stiffness*: impression of the flexural rigidity of the ski.
- *Torsion stiffness*: impression of the torsional rigidity of the ski.
- *Overall impression*: global evaluation of the qualities of the ski for slalom racing.

*Procedure.* The tests were carried out over 4 days under similar snow conditions: the slope was prepared and consisted of packed powder, promoting a good grip. The air temperature was between −6 and −14°C, and the snow temperature was approximately −15°C. All the test skis were prepared (base was waxed and edges were sharpened) by the same service-man before each test day. To ensure that they could focus on the skis' performance only (i.e. not including too many factors in the same study), the participants used their own ski boots.

(a)

1. Ease in initiating the turn 1 2 3 4 5 6 7 8 9 →
2. Accuracy 1 2 3 4 5 6 7 8 9 →
3. Self-steering 1 2 3 4 5 6 7 8 9 →

4. Tracking stability 1 2 3 4 5 6 7 8 9 →
5. Energy restitution (Acceleration) 1 2 3 4 5 6 7 8 9 →

6. Forgiveness 1 2 3 4 5 6 7 8 9 →
7. High speed quietness 1 2 3 4 5 6 7 8 9 →

8. Bending stiffness soft 1 2 3 4 5 6 7 8 9 → hard
9. Torsional stiffness soft 1 2 3 4 5 6 7 8 9 → hard

10. Overall impression poor 1 2 3 4 5 6 7 8 9 → good

(b)

1. Ease in initiating the turn 1 2 3 4 5 6 7 8 9 →
2. Accuracy 1 2 3 4 5 6 7 8 9 →
3. Grip 1 2 3 4 5 6 7 8 9 →

4. Quietness 1 2 3 4 5 6 7 8 9 →

5. Overall impression poor 1 2 3 4 5 6 7 8 9 → good

Figure 4. (a) Questionnaire handed out to participants testing the skis for their properties in carved turns. (b) Questionnaire administered to participants testing the skis for their properties in short, skidded turns.

Before they tested the skis, all the participants carefully read the questionnaire. The different points were discussed (always with the same experimenter) so that the skiers understood their meaning, and also to help them keep in mind which characteristics of the skis they should focus on. Additionally, special exercises specific to the different questions were developed and practiced by all participants before testing. All participants tested all four pairs of skis, the order of which was counterbalanced for each skier. The skiers were instructed to first perform a single run (approximately 2 – 3 min) with each pair of skis doing carving turns. Then the participants were asked to test the four skis in short, skidded turns. After each test run, they were asked to complete the questionnaire. A short break of 10 min separated each test run. No discussion between skiers during the test procedure was allowed.

*Statistics.* In the present analyses, the median was used as an estimate of centrality and the inter-quartile range was used as an estimate of variability. Standard deviations were computed over trials and participants. The relationships between the variables were described using the rank-order correlation coefficient of Spearman (*R*).

## Results

### *Correlation between skis' mechanical properties*

First, we determined the correlations between the various mechanical properties of the four pairs of skis. This revealed several significant correlations. $K$ correlated strongly with $f_2$ ($R = 0.98$, $P < 0.05$), the latter of which correlated strongly with $f_1$ ($R = 0.97$, $P < 0.05$). Furthermore, $K$ correlated strongly with $\lambda_1$ ($R = 0.99$, $P < 0.05$), and $T_f$ correlated strongly with $T_t$ ($R = 0.99$, $P < 0.05$). Finally, $\lambda_3$ (i.e. the damping coefficient of the first torsional mode) was negatively correlated with both $T_f$ ($R = -0.98$, $P < 0.05$) and $T_t$ ($R = -0.99$, $P < 0.05$).

### *Evaluation of the subjective data*

The responses to each item of the questionnaire are shown for carved turns (Figure 5) and short, skidded turns (Figure 6). The expert skiers used a larger range of rankings (mean for all the items = 5.45, variance = 2.4 for the carved turns; mean = 5.8, variance = 1.54 for the short, skidded turns), whereas the advanced skiers tended to rank close to the mean (mean = 5.2, variance = 1.1 for the carved turns; mean = 5.05, variance = 1.1 for the short, skidded turns). Indeed, the mean values were comparable whereas the variances differed, suggesting that the expert skiers were more certain of their judgements: given that they had more experience in the field they were able to judge more precisely whether they liked or disliked the skis, using the whole range of the 1 – 9 scale.

The expert skiers judged the four skis differently on almost all the criteria with the exception of "ease in initiating the turn" and "accuracy". They appeared especially sensitive to differences in "energy restitution" (Figure 7a) and "torsional stiffness" (Figure 7b).

The data for the expert skiers revealed perfect correlations (i.e. $R = 1.00$, $P < 0.05$) between "high speed quietness" during carving turns and "torsional stiffness", and between their "overall impression" of the skis during short, skidded turns and "self-steering". Moreover, their judgement of "energy restitution" correlated strongly with their judgement of both "high speed quietness" during carving turns ($R = 0.98$, $P < 0.05$) and "torsional stiffness" ($R = 0.98$, $P < 0.05$). Finally, their ranking of "tracking stability" also correlated with these same two criteria: "high speed quietness" during carving turns ($R = 0.96$, $P < 0.05$) and "torsional stiffness" ($R = 0.96$, $P < 0.05$).

The same analysis performed on the advanced skiers' data showed that "accuracy" during carving turns was positively correlated with "self-steering" ($R = 0.96$, $P < 0.05$). Furthermore, "ease in initiating the turn" during short, skidded turns was negatively correlated with "bending stiffness" ($R = -0.96$, $P < 0.05$). Finally, the advanced skiers' judgement of "grip" was highly correlated with both "ease in initiating the turn" during carving turns ($R = 0.96$, $P < 0.05$) and "energy restitution" ($R = 0.96$, $P < 0.05$).

### *Correlation between subjective ratings and objective data*

Since our main aim was to investigate how skiers judge variations in skis' mechanical properties, we correlated physical measures of the latter with the ratings of the participants. These correlations were quite different for the expert group and the advanced group. For the former, $T_f$ was strongly correlated with not only their judgement of "torsional stiffness" ($R = 0.96$, $P < 0.05$) but also their judgement of "high speed quietness" during the carving turns ($R = 0.96$, $P < 0.05$) and "energy restitution" ($R = 0.99$, $P < 0.05$). Furthermore, $T_t$ was also strongly correlated with "energy restitution" ($R = 0.98$, $P < 0.05$).

Judgement of "bending stiffness" by advanced skiers, on the other hand, was strongly correlated with the physical measure of bending, $K$ ($R = 0.96$, $P < 0.05$). Similarly, their judgement of "torsional stiffness" correlated with the physical measure of $T_t$ ($R = 0.97$, $P < 0.05$). Furthermore, their judgement of "grip" was strongly correlated with the torsion of the front part of the skis ($R = 0.96$, $P < 0.05$). Whereas the loss factor of the first resonance frequency, $\lambda_1$, showed a strong negative correlation with "accuracy" during short, skidded turns ($R = -0.97$, $P < 0.05$), it was positively correlated with advanced skiers' judgement of "high speed quietness" during carving turns ($R = 0.97$, $P < 0.05$).

## Discussion

The correlations between the skis' mechanical properties revealed that the results were (i) in perfect agreement with physical expectations (e.g. increased flexural rigidity leading to higher resonance frequencies), and (ii) absolutely consistent with the skis' construction. For reasons of confidentiality, however, details about (ii) cannot be discussed here.

When comparing the results of the subjective data with each other, it appeared that torsional stiffness was not only rated differently for each pair of skis, but was also linked to the key factors characterizing the quality of the skis. For instance, expert skiers rated similarly (high correlation) energy restitution and torsional stiffness (i.e. the stiffer the ski in torsion, the more energy was restituted in the transition phase from one turn to the next). This is usually perceived as an ability of the ski to perform well at the end of the turn, a characteristic that is of great importance in the context of slalom skis. Furthermore, expert skiers linked high torsional stiffness to quietness during carving turns, as well

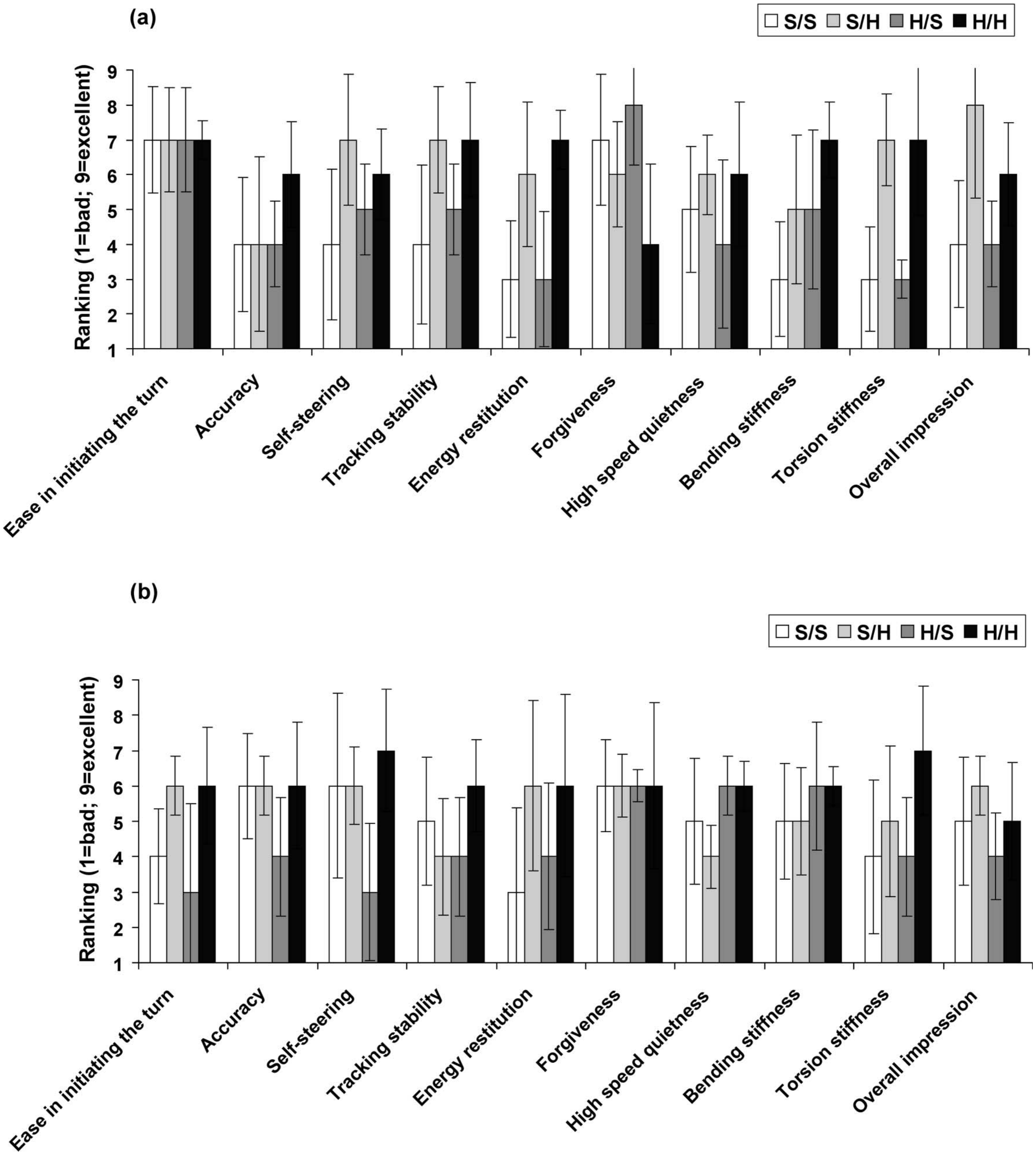

Figure 5. Mean values and variance of responses to each item of the questionnaire related to carved turns for (a) expert skiers and (b) advanced skiers. Combinations of flexural/torsional rigidity: HH = hard/hard, HS = hard/soft, SH = soft/hard, SS = soft/soft.

as to tracking stability. The latter is no surprise, since it is the torsional rigidity that makes the carving technique possible, carving depending on the capacity of the ski to follow the line "as if on rails" (i.e. without skidding). This particular result can thus be taken as proof that expert skiers are indeed able to judge the mechanical properties of skis accurately.

Regarding the correlation between subjective ratings and objective data, skis that combined low flexural rigidity with high torsional rigidity were generally highly rated in terms of their overall performance as slalom skis, a judgement that was independent of the skiers' proficiency (Figure 5). More specifically, many of the significant results were linked to the torsional rigidity of the skis. Indeed, all participants clearly discerned the differences in torsional rigidity (i.e. they rated the skis differently). With advanced skiers, the rating of the "grip" in short, skidded turns increased with increasing torsional rigidity. Once again, this made sense, since high torsional rigidity is a physical requirement for good grip. Moreover, the advanced skiers judged that it was easier to initiate a short,

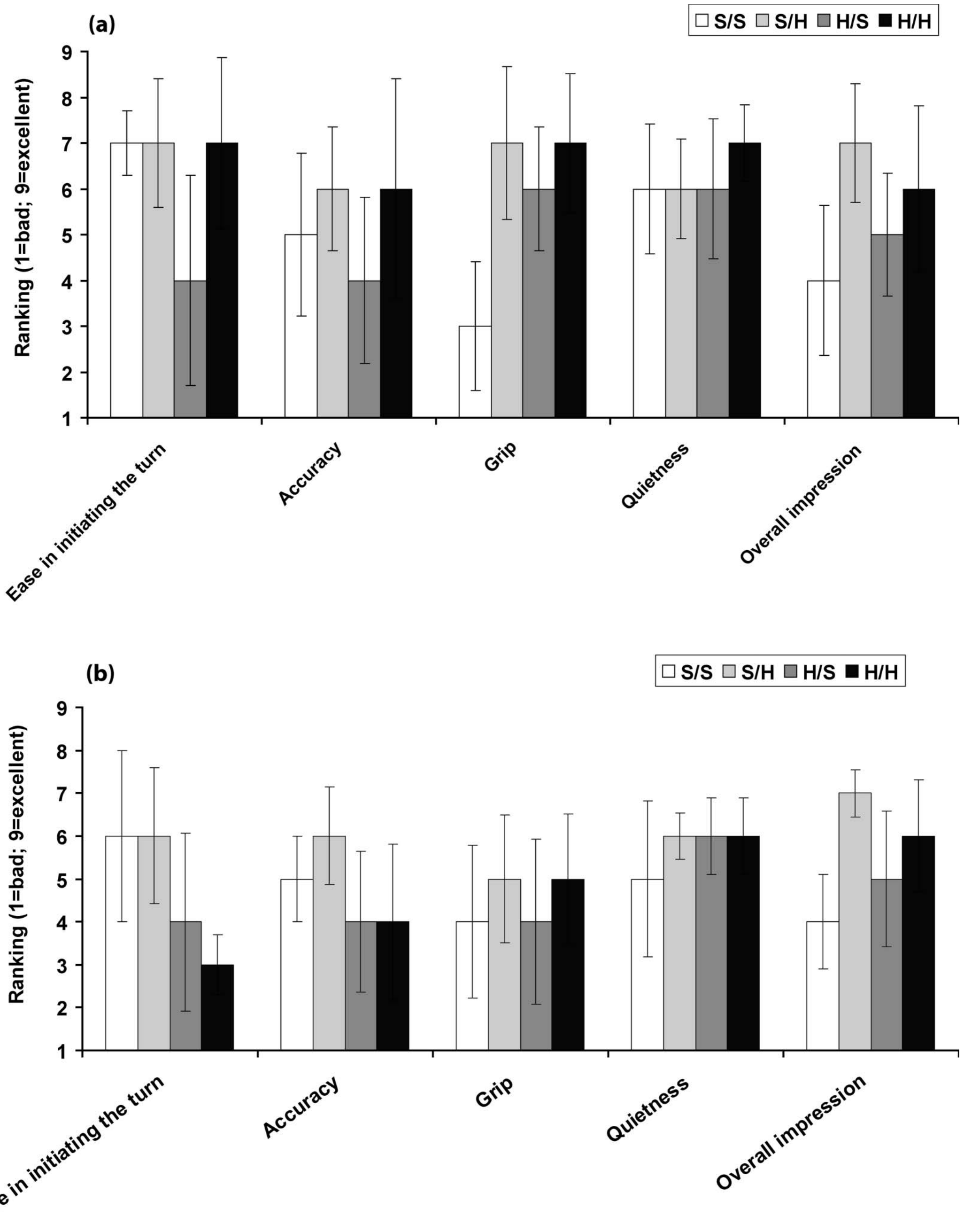

Figure 6. Mean values and variance of responses to each item of the questionnaire related to short, skidded turns for (a) expert skiers and (b) advanced skiers. Combinations of flexural/torsional rigidity: HH = hard/hard, HS = hard/soft, SH = soft/hard, SS = soft/soft.

skidded turn with skis that were more compliant in bending than with stiffer skis. This is because more power and a better technique are required to change from one ski edge to the other with a stiffer ski in flexion than with a softer one, which might explain why this factor did not appear to be as important for the expert skiers. Furthermore, only advanced skiers judged the skis' damping behaviour to differ among the four pairs: high damping of the first resonance frequency was found to have a negative influence on accuracy during short, skidded turns, while it had a positive influence on quietness at high speed. However, since the damping of the first resonance frequency and the flexural rigidity are highly correlated with one another, it is difficult to draw any conclusion from this result.

The fact that torsional rigidity had a stronger influence than bending rigidity on the participants' judgement may be linked to the higher relative differences in torsional rigidity between the "softest" and the "stiffest" skis used. Further studies would be required to clarify this point. We are also

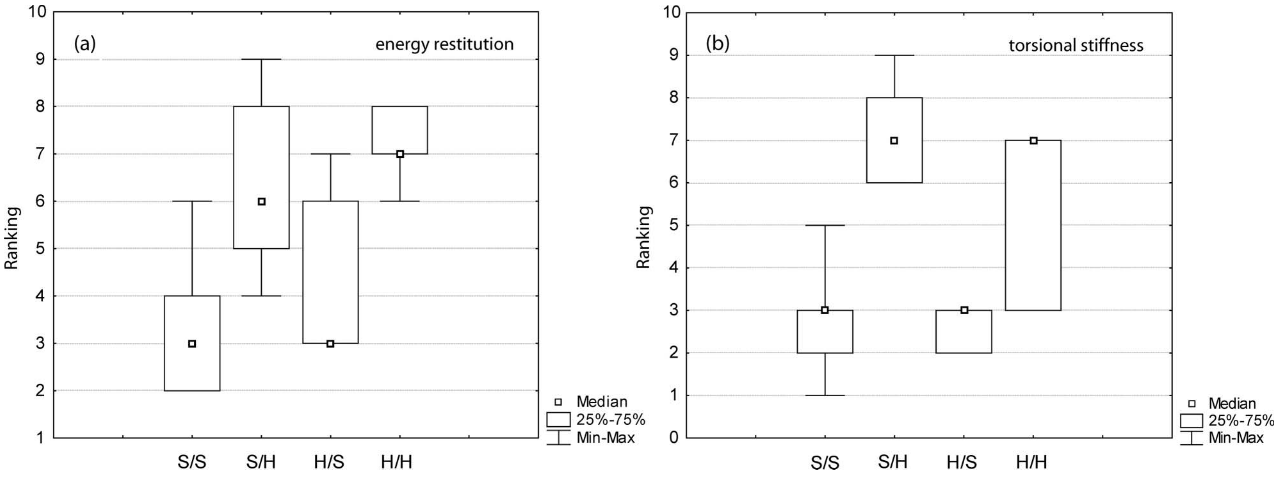

Figure 7. Boxplots showing median values and variability for each ski according to expert skiers' judgements of (a) energy restitution and (b) torsional stiffness in the case of carved turns. Combinations of flexural/torsional rigidity: HH = hard/hard, HS = hard/soft, SH = soft/hard, SS = soft/soft.

aware that the number of participants was limited. However, we decided that it was more important to keep the same environmental conditions for all participants, which limited the number of possible test days, and thus the number of skiers. It is important to note, however, that we do find significant results even with a small sample, which brings even more consistency to the results. Finally, it should be pointed out that all the results obtained in this study were strongly linked to (i) the ski type (slalom ski) and (ii) the snow type.

## Conclusion

Using four pairs of slalom skis specifically designed to differ between each other in mechanical properties, we found that skiers of different proficiency (expert and advanced level) all preferred the slalom skis with a high torsional rigidity and a low flexural rigidity. While correlations (Spearman) between the skis' mechanical properties and the perceived characteristics showed that expert skiers could judge differences between the skis more accurately than advanced skiers, the two groups differed in their ratings of certain characteristics. However, both groups were very sensitive to torsional rigidity and had no difficulties judging it in relation to the four sets of skis. While expert skiers considered a high torsional rigidity to have a positive effect on characteristics such as quietness at high speed or energy restitution in carved turns, advanced skiers judged stiff skis in torsion to have a positive influence on the "grip" during short, skidded turns. Moreover, advanced skiers also judged that highly damped first resonance frequencies led to a quieter ride at high speed, and that soft skis in flexion made it easier to initiate the short, skidded turns. Collectively, our data suggest that static and dynamic properties should be integrated into the design of new skis by systematically subjecting different skis to ratings by expert and advanced skiers. The present approach has been shown to be a powerful method for linking human judgement to the mechanical properties of sports equipment.

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