# MECHANICAL AND METABOLIC ENERGY ASPECTS OF DIFFERENT BINDING-BOOT SYSTEMS IN SKI-TOURING

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The purpose of this study was to analyse the effect of different ski touring equipment on the energy cost of ski-tourers during uphill walking with skis. The material was studied both from a mere mechanical aspect as well as from a metabolic point of view. For the metabolic study a total of 16 subjects completed several uphill walks with skis on a treadmill inclined 15° and an average walking speed of 2.5 km/h. During these uphill walks the average oxygen uptake was measured by Cosmed K4b2. The mechanical study was carried out by measuring mass, points of rotation and center of mass and calculating the mechanical energy cost of the diverse binding-boot systems. The results of the mechanical study, as well as the metabolic results went into the same direction, though the differences in metabolic energy cost between the diverse binding-boot systems were more distinct. The differences in energy cost among the bindings were significant while the difference regarding boots was not. Taking the results in consideration, the use of specific ski-touring equipment can reduce the energy cost of a ski-tourer which allows him to complete an ascent faster or save energy for the downhill run.

**KEY WORDS:** ski-touring, mechanical energy, metabolic energy, ski binding, ski boots.

**INTRODUCTION:** Ski-touring has become a very popular sport in alpine areas within the past twenty years. The athletes especially appreciate the long and relatively low-intensive ascents in quiet mountain areas and downhill skiing on ungroomed runs. In the last years competitions in this discipline have established and ski-touring is even planned as a demonstration discipline at the Winter Olympics 2006 in Torino. Due to the different functions the equipment in ski-touring differs substantially from common skiing equipment. The skis are shorter and lighter, the boots are lighter and equipped with devices to use them both, for walking and downhill skiing. The most distinct difference, however, pertains the bindings to guarantee both, the walking and downhill skiing function. Ski-touring bindings are equipped with a hinge joint in the toe unit of the binding to provide a rotation of the foot relative to the ski. The rear unit of the binding is designed to use it either in a loose position for walking or in a fixed position for downhill skiing. Currently different binding systems are available on the market. The solutions of the diverse systems to provide the walking and skiing function differ quite substantially and, therefore, might cause diverse energy costs during the ascent. The purpose of the study covers two aspects: Firstly, different binding systems and boots used in ski-touring should be analysed concerning the mechanical energy aspects during uphill walking. Secondly, it should be clarified if different mechanical energy consumption caused by diverse ski boots and ski bindings also affect the metabolic energy cost in ski-touring.

## METHODS:

**Equipment:** Three binding systems (A, B and C, Figure 1) and two ski boots (1, 2) have been analysed in this study. In bindings A and B, the rear part is rigidly connected to the toe unit so the whole binding has to be moved along with the boot during the walking movement. In binding C the toe and heel unit of the binding are not connected. The boots used along with this binding system are equipped with two holes on the medial and lateral side of the boot's toe part. Clamps on the toe unit of the binding fit into these holes and provide fixation of the boot to the toe unit supported by a spring. The heel unit is mounted to the ski. It can be rotated to provide either a loose heel for uphill walking or a fixation with the boot for downhill skiing. The two ski boots used in the study could be used along with all binding systems and differed in construction, shape and mass. Table 1 shows the mechanical properties of the bindings and boots used in the study.

Figure 1: Bindings for ski-touring: A (left), B (middle), C (right).

**Table 1 Mechanical properties of the bindings and the boots.**

| | binding A | binding B | binding C | boot 1 | boot 2 |
|---|---|---|---|---|---|
| Mass to lift [kg] | 0.825 | 0.900 | 0.000 | 1.705 | 1.550 |
| CoMx [m] | 0.228 | 0.191 | 0.000 | 0.193 | 0.188 |
| CoMz [m] | 0.011 | 0.008 | 0.000 | 0.098 | 0.092 |

**Mechanical energy of binding-boot systems for elevation:** The elevation of the boot-binding-system during uphill walking with skis proceeds in a rotation around the fixation point D located at the binding in the systems A and B and at the boot in the system C. Hence, the center of mass (CoM) describes a circular arc. For determination of the mechanical energy only the lift has been considered, the downward movement has been neglected. The lifting movement has been approximated by a half sine wave for the angular velocity ($\omega$) an angle of rotation ($\omega$ ) of 60° ( 0=0°, $\psi_1$=60°) and a duration of 240 ms. This approximation is based on a kinematic analysis of this particular movement. Based on this data the angular velocity can be calculated as a function of time $\omega$ t . The time integral of $\omega$t yields the angular displacement over time $\omega(t)$.

The entire system consists of the segments binding and boot. The coordinates of the system in the starting position can be calculated from the data in table 1. The angle $\alpha$ of the straight line between point of rotation (D) and the CoM relative to the horizontal can be determined by arctan(CoMz/CoMx). The coordinates of the CoM as a function of time can be calculated by $CoMx(t) = c \cdot \cos(a + \psi(t))$ and $CoMz(t) = c \cdot \sin(\alpha + \psi(t))$ with $c = |D - CoM|$.

The gravitational force in the CoM F [$F = (m_{binding} + m_{boot}) \cdot 9.81$] generates a torque M around D over time with $M(t) = F \cdot CoMx(t)$. The mechanical power P in relation to D over time can be determined by $P(t) = M(t) \cdot \omega(t)$. The time integral of P(t) over time yields the mechanical work done (energy used) to elevate the boot-binding system ($E = \int P(t)\, dt$) .

Metabolic energy in walking with different binding-boot systems

The metabolic energy cost was measured concerning three aspects in different studies with similar methodological design: 'bindings', 'boots' and 'long term'. The subjects were asked to walk on a treadmill inclined 15° with a ski-touring equipment at a walking speed of 2.5 km/h. The energy consumption was determined by measuring the oxygen uptake ($VO_2$) online using a Cosmed $K4b^2$.

In the study 'bindings' 16 subjects (experienced ski-tourers) walked uphill on the treadmill with the bindings A, B and C. All subjects used ski boot 1 and identical skis. The order of the conditions was randomised among the subjects. In each condition the subjects walked for at least 5 minutes in an oxygen steady state after a 20 min warm up on the treadmill. The breaks to change bindings lasted about 90 seconds and it needed about 3 minutes to reach a steady state again. The average oxygen uptake within 4 minutes for each binding condition was used for further data processing. The statistical analysis was carried out using a one-way ANOVA for repeated measurements with Bonferroni correction.

The general proceeding for the study on 'boots' was similar. This time 10 subjects walked with boots 1 and 2. All subjects used binding C on the same ski. The two different boot conditions were randomised among the subjects again. In both conditions the subjects walked for at least 5 minutes in an oxygen steady state after a 20 min warm up on the treadmill. The breaks to change the boots lasted about 3 minutes and it needed about 4 minutes to reach a steady state again. The average oxygen uptake within 4 minutes for each boot condition was used for

further data processing. For statistical analysis the t-test for paired samples was used.
To check if the differences that occurred in the 'binding' and 'boot' studies change over a longer period of walking time, the study 'long term' was carried out. 4 subjects walked with the lightest (C2) and one of the heavier boot/binding combinations (A1) for a total walking time of 90 minutes on the treadmill. This time the walking speed could be chosen individually (between 2.0 and 2.5 km/h) to guarantee that each subject could finish the 90 minutes programme. For further data processing the average oxygen uptake within 10 minute intervals was calculated. The first interval was not considered in the data processing to avoid artefacts due to the high variability in the warm up phase. The data were statistically analysed using a one-way ANOVA for repeated measurements.

**RESULTS:**

**Mechanical energy of binding-boot systems for elevation:** Table 2 shows the mechanical energy cost for lifting the boot-binding system from 0° to 60° within 240 ms once.

**Table 2 Mechanical energy for lifting the binding-boot systems.**

| Energy [J] | binding A | binding B | binding C | A/C [%] | B/C [%] |
|---|---|---|---|---|---|
| boot 1 | 3.51 | 3.38 | 1.96 | 79 | 72 |
| boot 2 | 3.31 | 3.18 | 1.76 | 88 | 81 |
| 1/2 [%] | 6 | 6 | 11 | | |

The sum of the mechanical energy generated by the hip-, knee- and ankle joint during one stance phase in uphill walking (without skis) at an inclination of 15° is approximately 80 J for an athlete with a body mass of 70 kg (Schwameder et al. 2000). Based on this data the relative difference between A and C was found to be 1.90% and between B and C 1.74% independent from the boot condition.

**Metabolic energy in walking with different binding-boot systems:** The results of the study 'bindings' are presented in table 3. The average oxygen uptake is highest in walking with binding A and lowest with binding C. Walking with binding A and B needs statistically more metabolic energy than walking with binding C. Binding A and B are not statistically different.

**Table 3 Oxygen uptake during uphill walking with skis on a treadmill; means (standard deviations) for three different bindings.**

| $VO_2$ [ml/kg/min] | binding A | binding B | binding C | A/C [%] | B/C [%] |
|---|---|---|---|---|---|
| boot 2 | 36.6 (2.3) | 36.3 (2.8) | 35.7 (2.6) | 2.6 * | 1.8 * |

The ski-boots used in the study 'boots' did not significantly affect the oxygen uptake during uphill walking with skis (table 4). The metabolic energy consumption was found to be 0.6% less with the lighter boot (boot 2) compared to the heavier one (boot 1).

**Table 4 Oxygen uptake during uphill walking with skis on a treadmill; means (standard deviations) for two different boots.**

| $VO_2$ [ml/kg/min] | boot 1 | boot 2 | 1/2 [%] |
|---|---|---|---|
| binding C | 35.8 (2.4) | 35.6 (2.4) | 0.6 |

Figure 2 shows the oxygen uptake in uphill walking with skis comparatively with the binding-boot combination A1 and C2 over time in the study 'long term'. The differences are between 4% and 5% with a trend to an increase with exercise time. The differences in the last three intervals are significant.

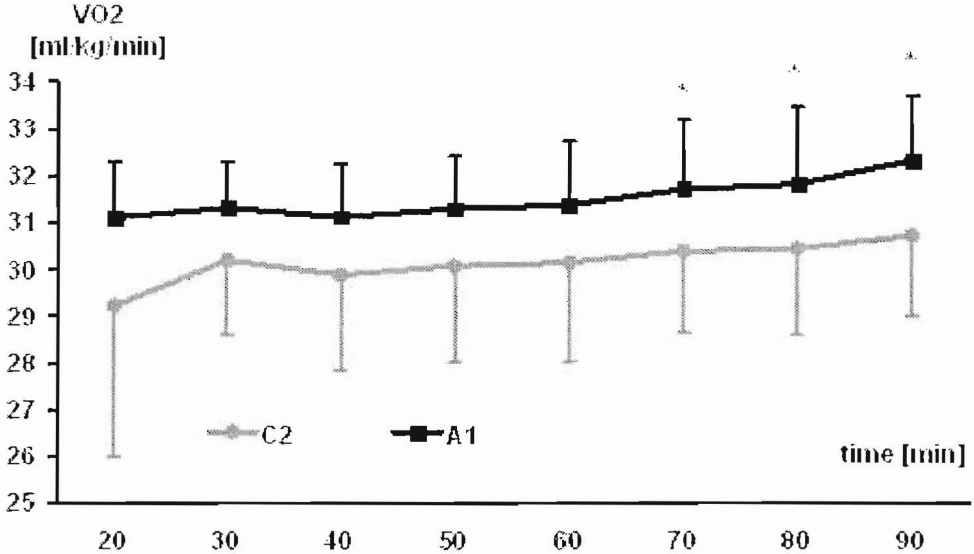


Figure 2: Oxygen uptake during uphill walking (90 min) with skis on the treadmill; means and standard deviations for two different binding-boot systems.

**DISCUSSION AND CONCLUSION:** The differences concerning the mechanical energy in the binding conditions were between 72% and 88%, while the differences between the boots were relatively small (6% - 11%). The results can be explained by the different locations of the point of rotation and by the different mass that has to be lifted in the diverse binding conditions during uphill walking with skis. These two aspects had the greatest effect on energy cost, while the mass of the boots only showed little influence on energy consumption.

Similar results were found concerning the metabolic energy cost for the diverse conditions. However, the differences are more pronounced. The major part of the observed differences in the metabolic energy cost can be attributed to the mechanical conditions presented above. The remaining differences can be related to the restricted mechanical model used. The following potential aspects have not been taken into consideration: the lowering of the binding after the lift, the total mass of the binding-boot system during the forward motion of the ski and different effects on the coordination pattern. The result of the long term study leads to the assumption that the differences in energy consumption, caused by the binding-boot systems, increase with ascent duration.

In conclusion diverse binding-boot systems affect the metabolic energy cost during uphill walking with skis and can primarily be explained by the different mechanical conditions. The results can directly be applied to the natural ski-touring situation. Specific ski-touring equipment can either result in lower energy cost for ascent which is a factor related to performance in competitive ski-touring or save energy for the upcoming downhill run which is particularly important for leisure ski-tourers.

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