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Title: Validation of portable 2D force binding systems for cross-country skiing

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Abstract

The aim of the present study was to design, construct, and scientifically validate a two-dimensional force measurement binding system for cross-country skiing. The system consists of two force measurement bindings. One binding was designed for analysing classic skiing (vertical and anterior-posterior [along the ski] force components) and the other one for skate (freestyle) skiing (vertical and medio-lateral [transverse to the ski] force components). Validation was accomplished by using a three step process 1) accuracy tests for the sensors in two temperatures, 2) sport-specific imitation jump test on standard force plates in a laboratory and 3) comparing the system against force measurement reference systems that are currently used when skiing on snow. During sport-specific imitation jumps, differences in peak forces and impulses between the classic binding and the reference systems ranged from 8.0 % to 19.9 % and were two to three times greater compared to differences between the skate binding and the reference systems (range: -5.9 to 5.5 %). However, high similarity coefficients were observed with both bindings (classic binding: 0.990 to 0.996; skate binding: 0.996 to 0.999) compared to the reference systems. Based on these results, the skate binding was shown to be fully valid for use in field measurements of skate skiing, whereas some improvements have to be performed in the construction and sensor placements for the classic binding (vertical as well as anterior-posterior force component).

1 Introduction

Force measurements in cross-country skiing have been conducted for over three decades using different methods. Two main approaches can be found from the earlier studies: 1) force measurements between the ski and the athlete with small force measurement plates or pressure insoles and 2) force measurements with systems buried under the snow. There are advantages and disadvantages to both approaches. With small force measurement plates attached to the skis, the forces can be measured in two [1-5] or three directions [6-10]. However, these kinds of force measurement plates add extra weight to the skis and although positioned close to the balance point of the ski they may still have a small effect on skiing. In addition, some limitations have been reported concerning the forces in medio-lateral and/or anterior-posterior direction [3,9]. Especially for analyses during roller skiing, strain gauges have been used and installed directly on the roller skies during classic skiing and skating measuring the forces in several dimensions [11-13]. Pressure insoles have been widely used in cross-country skiing research during the last decade due to the light-weight and minimal effect on the athletes' performances [14-17]. With pressure insoles, only the vertical force component can be measured and the measuring frequency of 100 Hz may be too low for some applications. The advantage of this method is the possibility to measure the center of pressure. Both force plates and pressure insole systems may influence athletes' performances due to the weight of the measurement systems (amplifiers, data loggers etc.). Data collecting and transmitting equipment are normally placed on a skier's waist with waist packs, while the included cables may slightly restrict movements and disturb skiing. However, the benefit of these systems is the possibility to measure several consecutive skiing cycles in one trial. In addition, these methods are not technique sensitive, so both skiing techniques (skating and classic) can be measured with these systems. Force platforms placed under snow allow an athlete to ski freely over the force measurement systems without any disturbing devices or cables attached. These systems allow measurement of only a few cycles per trial due to the length of the platform (6 m to 20 m) and it is in most cases only possible to investigate classic technique due to the construction of the system [2,18-20]. For skate skiing, Leppävuori [21] introduced a force measurement platform which was 2m long that could record one cycle per trial. In addition, measuring of skiing in different situations, e.g. varying track inclinations or the need of changing the measurement place, demands a great deal of time due to the big size and weight of those systems.

Classic technique with e.g. diagonal skiing technique can be analyzed with two dimensional force measurement systems since when moving straight forward along a classic skiing track only vertical as well as anterior-posterior (propulsive; along the ski) leg force components are mainly relevant. In contrast, skating techniques are more three-dimensional movements where all possible force components are important with a main focus on the vertical as well as the medio-lateral (transverse to the ski) force components. The medio-lateral direction of force is of special interest during skate skiing because the propulsive force is produced when the ski is edged. In a recent study [10] it was shown that the medio-lateral forces were higher using skis with a greater coefficient of friction, whereas no differences were observed in the vertical forces. This suggests that measuring only vertical forces is not enough to fully understand the requirements of skate skiing in different conditions and furthermore highlights the importance of measuring medio-lateral forces. In addition, with both vertical and medio-lateral force components a resultant ski force during skating can be calculated. Resultant forces from poles and legs are required in order to have the full benefit of three dimensional motion analyses. Using these two methods, it is possible to calculate the propulsive leg force component of skate skiing in any condition as described by Smith [22], acquiring the ski edging angle and the ski orientation angle from motion analyses and resultant forces from skis and poles. An accurate, valid, reliable and direct measurement of several leg force components combined with 3D kinematics will improve cross-country skiing specific motion analyses for technique optimization processes and the analyses of new ski or boot equipment, altogether in order to optimize skiing performance.

Even though forces have been measured in cross-country skiing with several different systems, there still is a great and from literature clearly justified need for a valid, accurate and light system synchronously measuring several force components. Such a system may respond to the high-level requirements of today's elite as well as recreational skiing. Earlier attempts in this working group to develop a 3D-force measurement system were partly successful. The constructed force binding could be easily transferred from one ski to another allowing for effective testing of different skis and athletes within a short period of time [9,10]. However, even though the system proved to be reliable for vertical and medio-lateral forces, there were still limitations concerning the measurement of the anterior-posterior forces acting along the ski [9] and additionally, there was still a need to make the system lighter and easier to use. Therefore, the aims of this study were to further develop the force measurement system by designing and building two separate two dimensional (2D) force bindings, one for kinetic classic skiing and one for skate skiing analyses. The functionality of these new systems should be tested 1) using accuracy tests separately for each force component with the sensors mounted in the front or rear parts of the binding and under lab as well as ski tunnel conditions, 2) using skiing imitation jump tests on standard force plates in a laboratory and 3) by skiing with the new system and comparing it against reference systems that are currently used in research investigating skiing on snow.

2 Materials and Methods

In this project, a custom-made force measurement system for cross-country skiing was designed and built. In order to test the functionality and validity of the new system, a three-step process was conducted. In the first step, the accuracy of the strain gauge sensors, mounted on the aluminum front and rear parts of the binding were tested separately and this was done in three temperature and mechanical stress conditions. In the second step, the system was compared against a standard 3D force plate in four different sport-specific imitation jumps in a laboratory and with and without extra load carried by the skier. Finally, the system was compared against systems that are currently being used during scientific measures in classic as well as skate skiing on snow.

2.1 Force binding

A custom-made force measurement system designed as a force binding (Figure 1) for recording several spatial components of forces during cross-country skiing was developed by the Neuromuscular Research Center, University of Jyväskylä, Finland. The force measurement system consisted of two force bindings in which one binding was specifically designed for analysing classic skiing techniques (classic binding) and the other for skate skiing techniques (skate binding). Both bindings contained parts for measuring front and rear foot forces in 2 dimensional spaces. Both bindings measured vertical forces (F_Z) in front and rear parts however the classic binding additionally gauged the anterior-posterior (along the ski, F_Y) force components and the skate binding the medio-lateral (transverse to the ski, F_X) force components (Figure 2). Based on experiences from the first 3D versions of the force binding [3,9] this separation was made to keep the construction of the plates more simple, to have less cross-talk between the sensors and so to get more accurate signals. The force binding was designed to move easily from one pair of skis to another by using the Rottefella (Rottefella as, Klokkarstua Norway) NIS (Nordic Integrated System) system. The NIS system allows removing or changing the place of the force binding without using screws. The total weight of both force bindings (classic plus skate binding) was 980 g, with 200 g weight for each rear and 290 g for each front part. Therefore the total added weight for one ski was 490 g. The total weight of the data capturing and transmitting equipment was 1050 g, which was distributed in parts as follows: amplifier 280 g; A/D-card and wireless transmitter 440 g; and battery pack 330 g that allows for several hours of measuring in cold conditions. The total weight of the whole measurement system was 2030 g. The used sensors mounted in the aluminum bodies of all rear and front parts of the force binding were based on resistance strain gauge technology where the resistance of the strain gauge is changed when it is stretched or compressed. A change in resistance caused a change in voltage over the gauge and these changes were comparable to changes in the applied force. In order to have reliable results, all force components were measured with a 4 strain gauge full bridge circuit. Signals were pre-amplified inside the force binding and transferred via wires to an amplifier (8-channel ski force amplifier, Neuromuscular Research Center, University of Jyväskylä, Finland). The amplifier was connected by separate cables for each force component (altogether 8 signal cables and one ground cable) for capturing data with the desired system. The amplifier was connected to a National Instruments wireless data acquisition and transmitting system, which consists of an A/D converter (sampling rate 1 kHz, NI 9205, National Instruments, Austin Texas, USA) and a wireless transmitter (WLS-9163, National Instruments, Austin Texas, USA). Data was transferred via WiFi to a receiver computer equipped with special data collecting software (LabVIEW 8.5; National Instruments, Austin Texas, USA).

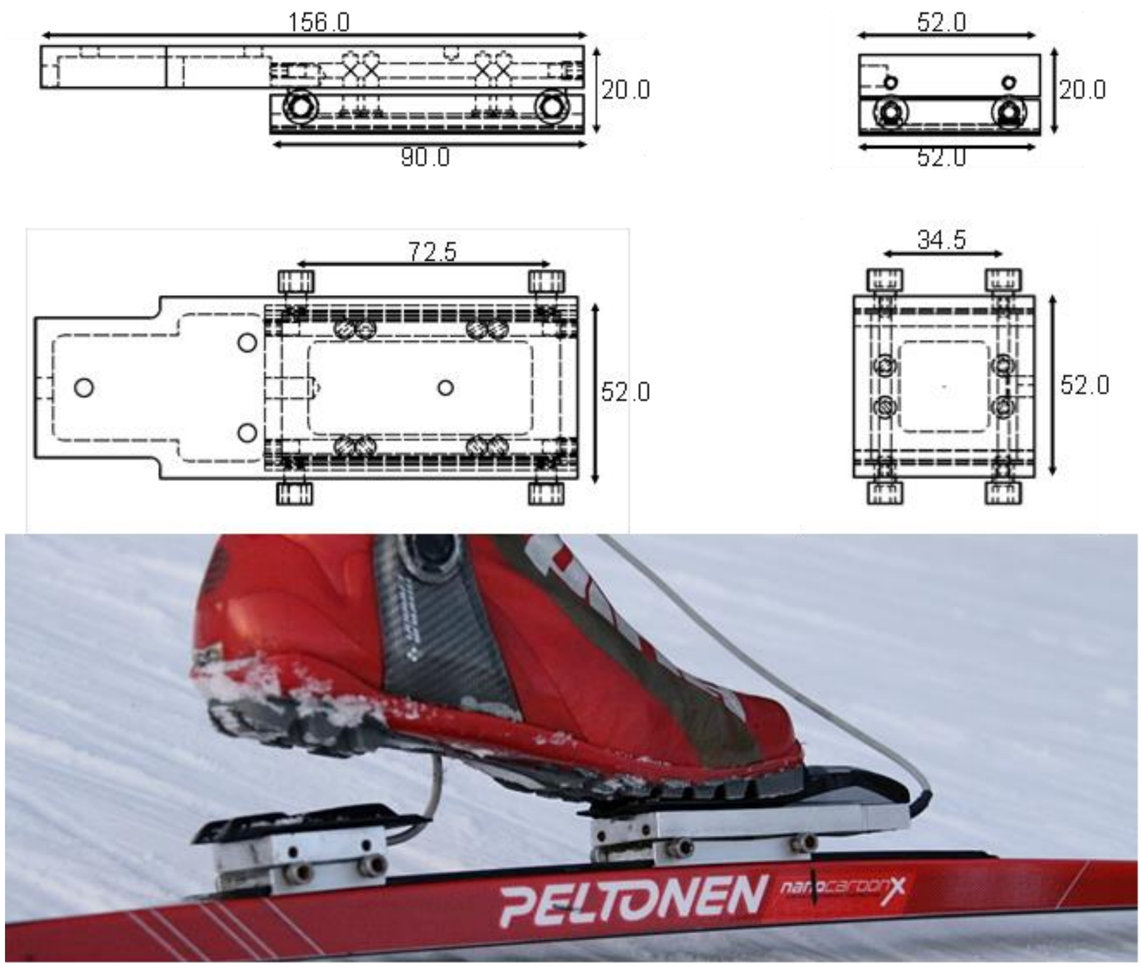

Fig. 1 Photograph and design drawing of the developed force measurement binding for cross-country skiing with dimensions of the front and rear part of the binding

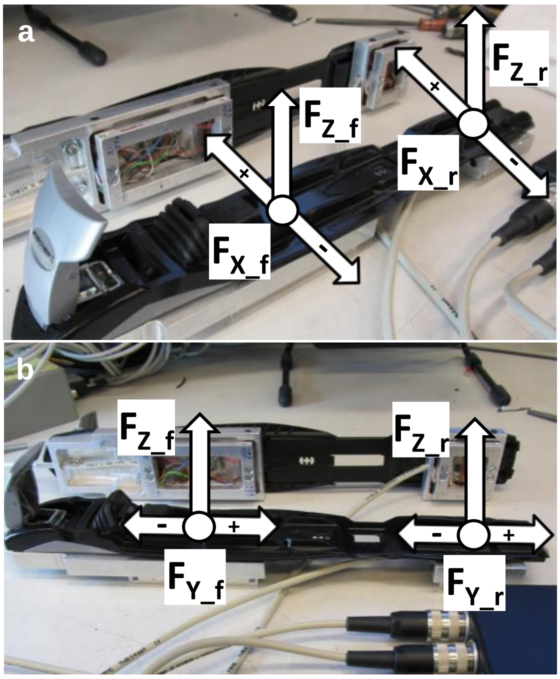

Fig. 2 (a) Vertical (F_Z) and medio-lateral (transverse to the ski) (+/- F_X) force components (skate binding) and (b) vertical (F_Z) and anterior-posterior (along the ski) (+/- F_Y) force components (classic binding) measurable separately by the front (f) and the rear (r) parts of both bindings

2.2 Calibration device

The calibration and the accuracy measurements for the rear and front parts of the force bindings were conducted with a special calibration device (Figure 3). The calibration device consisted of an amplifier, a screw vice where a commercial force sensor (Raute precision TB5, Nastola Finland) used as calibration sensor, was attached and an aluminum body where one part of the force binding was attached. The screw vice and body were attached to a thick aluminum base plate. The aluminum body could be attached to the base plate in three different positions to make the calibration of all three force components possible (Figure 3 a and c). The calibration sensor used as reference sensor and the amplifier were tested and calibrated in an accredited laboratory for force measurements (MIKES: The Centre for Metrology and Accreditation, Kajaani, Finland.). This sensor was confirmed to be reliable in the range of 0 to 1000 N with uncertainty ranging from 0.01 to 0.09 %. The calibration device was used in the accuracy tests during the first step of the validation process.

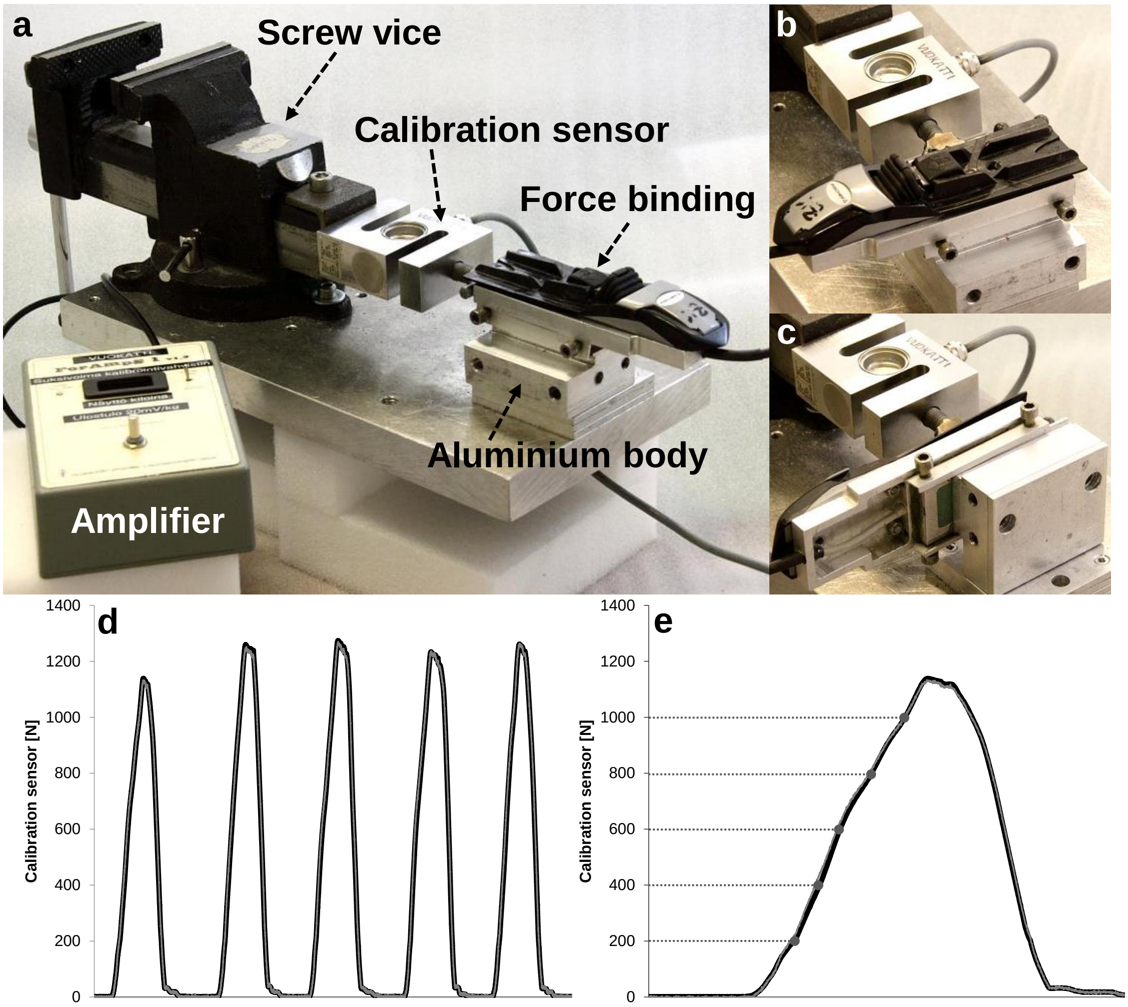

Fig. 3 Experimental set up for the calibration of the different force binding sensors: Adapted screw vice with mounted high precision reference sensor (Raute precision TB5, Nastola, Finland) and a part of the force binding with the amplifier, all mounted on a rigid aluminium body (a). The calibration sensor is pressed five times in succession (d) against the (a) anterior-posterior (F_Y), (b) medio-lateral (F_X) and (c) vertical (F_Z) force binding sensors determining voltage response at five increasing loads (e)

2.3 Reference systems in laboratory and field measurements

Sport-specific imitation jumps conducted during the second step of the validation process were performed in a laboratory over a 10 m long force plate row (8 plates of 1.25 x 0.60 m with natural frequency 180 ± 10 Hz for the vertical force component and 130 ± 10 Hz for the anterior-posterior force component, linearity ≤ 1%, cross-talk ≤ 2%; Raute Precision, Finland). The used force plate was based on strain gauge technology and has been used in numerous running studies, e.g. by Mero et al. [23].

In the third step of field measurements the following reference systems currently being utilized during scientific measures in classic as well as skate skiing on snow were brought to use: for classic skiing (diagonal style) the constructed force binding system was compared with a 20 m long force platform system (Neuromuscular Research Center, University of Jyväskylä, Finland), which consists of four parallel series of force plates for both skis and poles. The platform was composed of twenty 1 m long force plates which measure vertical (Fz) and anterior-posterior (Fy) components of force simultaneously along the platform from rows under skis and poles. These 1 meter long plates were connected to each other electrically in series row by row and voltage response was recorded with 1000 Hz. The measurement system was described in detail by Vähäsöyrinki et al. [20]. For comparing the force binding during skate skiing, a Pedar Mobile System (Novel GmbH, Munich, Germany) was used as a reference system. This system measures vertical ground reaction forces with pressure insoles, which include 99 capacitive sensors in each insole using a measurement frequency of 100 Hz. The insole data was transmitted via wires to a data logger. The calibration of the Pedar Mobile system was conducted using a special Pedar calibration device and these procedures were described in detail in several earlier cross-country skiing studies [14,15].

2.4 Accuracy measurements of the force binding sensors

The accuracy of the new force measurement system was tested by investigating the linearity and the repeatability of the force binding in calibration measurements in three different conditions against a calibration device: 1) laboratory (+22° centigrade); 2) ski tunnel (-5° centigrade); 3) 1 hour skiing in ski tunnel (-5° centigrade). In the calibration measurements, the rear and front parts were tested separately, each for both respective force components (Figure 2 a and b) in all described conditions which were a) pre and post measurements at 2-hour intervals in a laboratory as well as in a ski tunnel and b) also before and after 1 hour of skiing. The measurement equipment was placed and kept in the laboratory as well as in the ski tunnel for several hours before the measurements in order to be properly adapted to the temperature in each condition. The calibration for all components of forces was conducted by loading and unloading the appropriate binding part five times with each loading and unloading cycle lasting for approx. 2 seconds (Figure 3 d and e). To simulate the forces during natural skiing conditions all parts of the binding (all force components) were calibrated by 5 loads increasing by 200 N, 100 N and 50 N, up to 1000 N, 500 N and 250 N, respectively (Figure 3 e). Voltage response from the force binding data at appropriate points from five curves were collected and averaged. Figure 3 e shows an example of one calibration curve with appropriate points from the calibration sensor.

For linearity calculations, averaged values from the calibration sensor and the force binding were represented in the XY-coordinate system and a linear regression curve was drawn through all five points and R^2 values were calculated. Conversion factors to Newton were calculated from all five points with equation 1. A general conversion factor for each binding part was then achieved by calculating the average value of these five points.

$$\frac{F_{Calib}}{F_{Binding}} \tag{1}$$

Where F_{Calib} is the absolute (Newton) value from the calibration sensor and $F_{Binding}$ is the voltage value of the force binding.

The repeatability of the system was tested by calculating the relative difference of the conversion factor between pre and post tests for all the channels. These measurements were done to reveal the system's repeatability in two different constant temperatures. In addition, repeatability measurements were conducted to clarify the effect of mechanical stress (1 hour skiing) on the functionality of the force binding.

2.5 Comparison measurements during different jumps

In order to test the force binding in more applied situations, different modes of jumps simulating dynamic situations as well as diagonal and skate skiing were performed by one highly skilled male, National level cross-country skier: age = 44 years; height = 187 cm; body weight = 85 kg. A single subject design was chosen in order to keep the variability low between single imitation jump trials and thereby increasing the power for difference detection between all compared systems. Jumps and especially imitation jumps with skies plus force binding were and are highly demanding from a coordination point of view and had to be extensively trained properly even by the highly experienced skier. The individual-subject-analysis design was also used because the variations, especially in the used jump tasks, were considered to be the result of different strategies to perform the same imitation task by individual subjects, and not the result of more or less variations among individuals [24]. The skier was highly familiar with imitation exercises and with diagonal and skate skiing on skis during both training and testing. The athlete was fully informed about the nature of the study and procedures before giving his written informed consent to participate. The methods used and the experimental protocol of the study were approved by the University of Jyväskylä Ethics Committee. All jumps were performed on a force plate (Raute Precision, Finland). During all jumps including diagonal skiing and skating imitation jumps, the force bindings were attached to the skis and the subject used ski boots to better simulate a real skiing situation. Four kinds of jumps were done: squat jumps (SJ), counter movement jumps (CMJ), diagonal jumps (DJ) and skate jumps (SkJ). In all jump situations, absolute value signals from the front and back parts of the force binding were summed and compared to the force plate used as reference system.

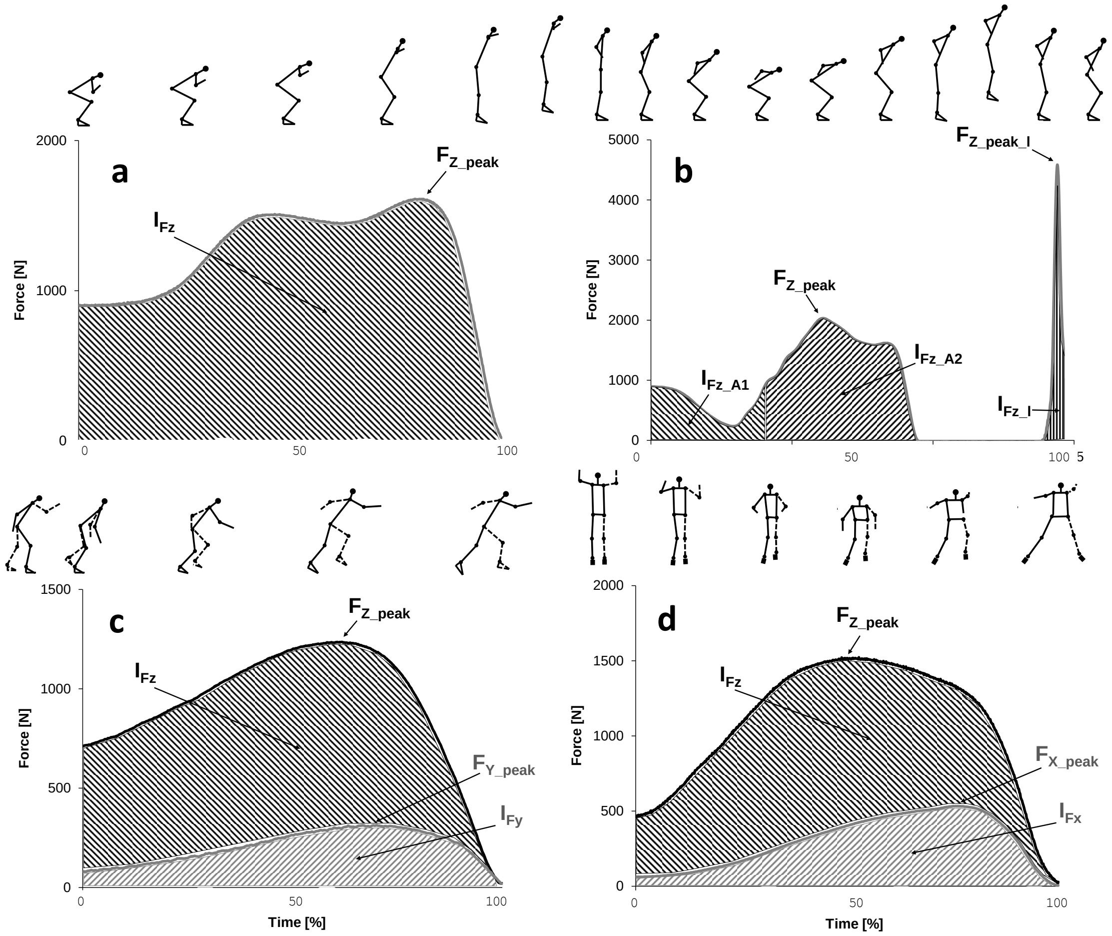

Fig. 4 Definitions of force variables during the two-legged squat (a) and countermovement (b) jumps and one-legged diagonal (c) and skating (d) imitation jumps in the lab

F_{Z_peak}, vertical peak force; I_{Fz_A1}, impulse of vertical force calculated for area 1 below the force curve (A1 = unweighting phase during CMJ); I_{Fz_A2}, impulse of vertical force calculated for area 2 below the force curve (A2 = impulse of force in deceleration + acceleration phase during CMJ); $F_{Z\_peak\_l}$, vertical peak force during landing impact; I_{Fz_l}, impulse of vertical force during landing impact; I_{Fz}, impulse of vertical force; F_{Y_peak}, anterior-posterior peak force; I_{Fy}, impulse of anterior-posterior force; F_{X_peak}, medio-lateral peak force; I_{Fx}, impulse of medio-lateral force

SJ and CMJ (Figure 4 a and b) were performed standing on and jumping from the force plate with both legs. The sum of the vertical signals from both types of force bindings were compared to the vertical signal from the force plate. From CMJs, landings were also analysed and compared to the force plate signal. DJs were performed in anterior-posterior (forward) direction on the force plate with one leg imitating the diagonal stride push-off phase (Figure 4 c). Vertical and anterior-posterior force components of the classic binding were analysed and compared to the corresponding signals of the force plate. SkJs were performed in the medio-lateral direction on the force plate (Figure 4 d) with one leg imitating the skate skiing push off phase. During SkJs the ski plus force binding were distinctly edged. In order to have comparable data from the force binding and the force plate, the following calculations were used for the vertical (equation 2) and medio-lateral (equation 3) directions (Figure 5). The calculations are based on ski edging angle analyses, which was acquired with a high-speed camera at 100 Hz (NXR-NX5E, Sony, Tokyo, Japan) and by using a specific 2D video analysis software (Dartfish, Fribourg, Switzerland).

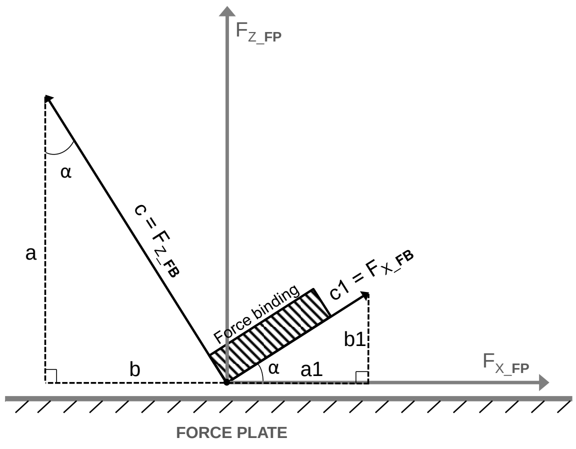

Fig. 5 Geometric scheme for the conversion of the vertical and medio-lateral binding forces (F_{Z_FB}; F_{X_FB}) during skating imitation jumps into vertical and medio-lateral force plate forces (F_{Z_FP}; F_{X_FP}) based on trigonometric functions in the right-angled triangle (equations 2 and 3)

$$F_{Z\_FP} = F_{Z\_FB} * \cos\alpha + F_{X\_FB} * \sin\alpha \tag{2}$$

$$F_{X\_FP} = F_{Z\_FB} * \sin\alpha + F_{X\_FB} * \cos\alpha \tag{3}$$

Where F_{Z_FP} and F_{X_FP} stand for the vertical and medio-lateral force components of the force plate and F_{Z_FB} and F_{X_FB} for the vertical and medio-lateral force components of the force binding. The calculations are also shown in Figure 5. From SkJs the calculated vertical and medio-lateral force components measured by the skate binding were compared to the vertical and medio-lateral signals from the force plate. If yaw rotations were observed between ski and force plate during SkJs, the particular jump was discarded from the results.

In all jump tests, each jump was carried out with 20kg extra load and without extra load to simulate heavier skier and/or stronger push offs. From each situation (SJ, CMJ, DJ and SkJ with and without extra load) 10 jumps were recorded for further analysis with both the systems (force binding and force plate). Peak forces and impulses (Figure 4 a to d) were calculated and absolute and relative differences between systems were investigated. In addition, similarity coefficients between the force binding and the force plate were calculated using Taylor polynomials [25] to show the similarity of the response between systems.

2.6 Comparison measurements during diagonal skiing and skating on snow

Finally the functionality of the force binding was tested in a skiing situation on real snow with diagonal skiing and skating techniques. In the skiing tests, the absolute signals from the front and rear part of the binding were also summed for achieving comparable signals to the used reference systems. The classic binding was tested using classic skiing diagonal stride technique on a 20 m long force platform system [20]. Vertical and anterior-posterior force components of the classic binding were compared to corresponding force signals from the long force platform. For skate skiing the V2-technique [22] was used when the skate binding was compared to the described pressure insole system. Pressure insoles measure only vertical forces and therefore only vertical forces could be compared between the systems. Due the lack of measurement systems, the medio-lateral direction could not be compared for the on snow skiing situation. With both techniques, the same skilled cross-country skier used medium speed (approx. 4 m/s for classic and 5 m/s for skating). With both skiing tests, again 10 subsequent cycles were averaged and analyzed and similarity coefficients were calculated.

Table 1 Comparison of the conversion factors (Volt to Newton) from two-time calibration measurements with a 2 hours break in between (pre vs. post) in three different conditions, i.e. in 1) the laboratory (+22°), 2) the ski tunnel (-5°) and 3) the ski tunnel (-5°) with 1 h skating (mechanical load) in between

Sensors	Lab (+22 °C)			Ski_Tunnel (−5 °C)			Ski_Tunnel (−5 °C) 1 h skating		
	Pre	Post	$Diff_{rel}$ (%)	Pre	Post	$Diff_{rel}$ (%)	Pre	Post	$Diff_{rel}$ (%)
SB sensors									
F_{Z_front}	1,237 ± 4	1,242 ± 8	0.4 ± 0.6	1,247 ± 10	1,242 ± 5	−0.4 ± 1.0	1,244 ± 4	1,297 ± 11	4.0 ± 1.9
F_{Z_rear}	1,166 ± 20	1,138 ± 16	−2.4 ± 0.9	1,133 ± 16	1,163 ± 32	2.5 ± 1.7	1,203 ± 30	1,194 ± 13	−0.7 ± 1.7
F_{X_front+}	1,274 ± 15	1,259 ± 20	−1.2 ± 0.9	1,242 ± 7	1,243 ± 14	0.1 ± 1.6	1,257 ± 21	1,217 ± 8	−2.0 ± 0.9
F_{X_front-}	−1,215 ± 23	−1,227 ± 33	−0.9 ± 1.4	−1,265 ± 26	−1,277 ± 8	0.9 ± 1.8	−1,272 ± 8	−1,273 ± 9	0.1 ± 1.7
F_{X_rear+}	1,279 ± 9	1,316 ± 19	2.8 ± 1.3	1,259 ± 16	1,209 ± 41	−4.2 ± 1.1	1,220 ± 11	1,211 ± 3	−0.8 ± 0.6
F_{X_rear-}	−1,247 ± 17	−1,298 ± 22	3.9 ± 1.8	−1,248 ± 16	−1,251 ± 9	0.3 ± 2.0	−1,217 ± 15	−1,243 ± 4	2.1 ± 1.4
CB sensors									
F_{Z_front}	1,211 ± 35	1,208 ± 29	−0.3 ± 0.5	1,214 ± 26	1,213 ± 23	0.0 ± 0.6	1,211 ± 22	1,216 ± 21	0.4 ± 0.3
F_{Z_rear}	1,246 ± 21	1,260 ± 15	1.0 ± 1.5	1,159 ± 12	1,184 ± 9	2.1 ± 0.5	1,496 ± 19	1,644 ± 32	9.7 ± 3.2
F_{Y_front-}	−1,137 ± 30	−1,155 ± 13	1.5 ± 2.9	−1,202 ± 14	−1,180 ± 29	−1.9 ± 2.2	−1,201 ± 11	−1,236 ± 17	3.6 ± 0.3
F_{Y_rear-}	−1,226 ± 24	−1,267 ± 40	3.2 ± 3.5	−1,239 ± 32	−1,277 ± 49	2.9 ± 1.7	−1,249 ± 44	−1,365 ± 48	8.7 ± 1.2

Values are mean ± SD (5 calibration measurements per sensor and condition)

$Diff_{rel}$ relative difference of conversion factors between two measurements, *SB* skating binding, *CB* classic binding, F_{Z_front} vertical force—front part, F_{Z_rear} vertical force—rear part, $F_{X\_front+/-}$ positive and negative medio-lateral force—front part, $F_{X\_rear+/-}$ positive and negative medio-lateral force—rear part, F_{Y_front-} negative anterior–posterior force—front part, F_{Y_rear-} negative anterior–posterior force—rear part

2.7 Data proceeding and statistical analyses

All data processing was conducted using IKE-master v. 1.34-software (IKE Software Solutions, Salzburg, Austria) and descriptive statistics with mean values and standard deviations were calculated using Microsoft Office Excel 2010 (Microsoft Corporation, Redmond, Washington, USA).

Similarity coefficients were calculated using MATLAB (The MathWorks, Natick, MA, USA) from time normalized curves between the force binding and the reference systems. In contrast to standard correlation coefficient calculations for time-discrete values, similarity coefficients are used with time series and they are mathematically based on Taylor polynomials [25]. The similarity coefficients were classified as follows -1 < similarity <1, where -1 means entirely contrary time histories, 0 means no similarity, and 1 means high similarity.

Table 2 Comparison of force variables between the cross-country skiing specific force bindings and a standard force plate during squat and countermovement jumps without and with 20 kg extra weight

Variables	Condition			
	FB	FP	$Diff_{abs}$ (N)	$Diff_{rel}$ (%)
SJ				
F_{Z_peak} (N)				
+0 kg	1,636 ± 80	1,613 ± 47	23 ± 40	1.4 ± 2.4
+20 kg	1,735 ± 44	1,764 ± 37	−29 ± 22	−1.6 ± 1.2
I_{Fz} (Ns)				
+0 kg	765 ± 6	738 ± 5	27 ± 4	3.6 ± 0.5
+20 kg	883 ± 9	863 ± 5	19 ± 7	2.3 ± 0.8
CMJ				
F_{Z_peak} (N)				
+0 kg	2,199 ± 91	2,078 ± 90	121 ± 21	5.9 ± 1
+20 kg	2,209 ± 91	2,106 ± 84	104 ± 17	4.9 ± 0.8
I_{Fz_A1} (Ns)				
+0 kg	173 ± 30	152 ± 28	21 ± 4	14.1 ± 2.8
+20 kg	246 ± 25	228 ± 25	18 ± 3	8.0 ± 1.5
I_{Fz_A2} (Ns)				
+0 kg	831 ± 23	789 ± 18	42 ± 6	5.3 ± 0.7
+20 kg	1,091 ± 23	1,044 ± 19	47 ± 7	4.5 ± 0.6
$F_{Z\_peak\_l}$ (N)				
+0 kg	5,194 ± 818	5,692 ± 988	−498 ± 195	−8.5 ± 2.3
+20 kg	4,840 ± 489	5,216 ± 553	−376 ± 115	−7.2 ± 1.9
I_{Fz_l} (Ns)				
+0 kg	145 ± 8	146 ± 8	−1 ± 1	−0.2 ± 0.9
+20 kg	157 ± 12	158 ± 11	−1 ± 1	−0.6 ± 0.5

Total binding forces are calculated as sum of all part forces (front and rear sensors) and both bindings (classic and skating binding) when jumping from the force plate with both skies/bindings fixed on the feet

Values are mean ± SD (10 repetitions per jump mode and condition)

FB force binding, *FP* force plate, $Diff_{abs}$ absolute difference between systems, $Diff_{rel}$ relative difference between systems, *SJ* squat jump, *CMJ* countermovement jump, F_{Z_peak} vertical peak force, I_{Fz} impulse of vertical force, I_{Fz_A1} impulse of vertical force calculated for area 1 below the force curve (A1 = unweighting phase during CMJ), I_{Fz_A2} impulse of vertical force calculated for area 2 below the force curve (A2 = impulse of force in deceleration + acceleration phase during CMJ), $F_{Z\_peak\_l}$ vertical peak force during landing impact, I_{Fz_l} impulse of vertical force during landing impact

3 Results and discussion

3.1 Accuracy of the force binding sensors

The accuracy tests showed high linearity in all situations (pre and post tests in the laboratory, ski tunnel and 1 hour skiing) with the range of R^2 values from 0.9981 to 1.0000 where the lowest values were observed after one hour of skiing in the rear part of the classic binding. The repeatability results between pre and post tests in three different conditions (laboratory, ski tunnel and 1 hour skiing) are shown in Table 1. In the laboratory tests, the highest difference in the conversion factors between pre and post tests were 3.9 % (skate binding, rear part, medio-lateral direction) with the range of all sensors varying between -2.4 % and 3.9 %. The repeatability measurements in the ski tunnel revealed equal differences compared to laboratory measurements with the largest difference of -4.2 % (skate binding: rear part, medio-lateral force component) and the range of all sensors varying between -4.2 % and 2.9 %. One hour of skiing caused greater differences in the conversion factors between pre and post tests compared to previous measurements resulting in 9.7 % as the largest value (classic binding: rear part, vertical force component) and with a range of -2.0 % to 9.7 % for all sensors. In addition, conversion factor levels were larger in this rear force channel compared to other tests (laboratory and tunnel tests without skiing) while conversion factor levels in other channels remained rather constant, although the reason for this is unclear. These results suggest that skiing had some mechanical effects on the rear part sensor of the classic binding with no negative effects found for the constructed skate binding. This was possibly due to a different construction and placing of the strain gauges, which probably led to a different level of sensitivity to mechanical loading between the bindings.

3.2 Comparison of force binding to force plate during jumps

SJ and CMJ were performed with both legs on the force plate and signals from both bindings were summed to obtain the total vertical force, which was comparable to the vertical force component of the force plate. Results of SJ and CMJ are presented in Table 2 and differences are always shown and discussed between force plate and force binding. The relative differences in maximum vertical forces were greater for CMJ (approx. 6 %) compared to SJ (-1.6 to 1.4 %). The differences in impulses of force were similar during SJ (approx. 3 %) and deceleration-acceleration phase of the CMJ (approx. 5 % for area [A] 2, Figure 4b). The greatest differences in CMJ were observed in the impulse of force during the unloading phase (8 % to14 %, area [A] 2, Figure 4b). Due to the lower absolute values during the unloading phase, the relative differences were greater for A1 compared to A2. All in all, the absolute differences stayed quite constant (Figure 6 a and d, Table 4) during both jumps with mean absolute differences for SJ of approx. 74 N and for CMJ of approx. 77 N indicating that the error was constant during jumps and the movement itself was not affecting the error.

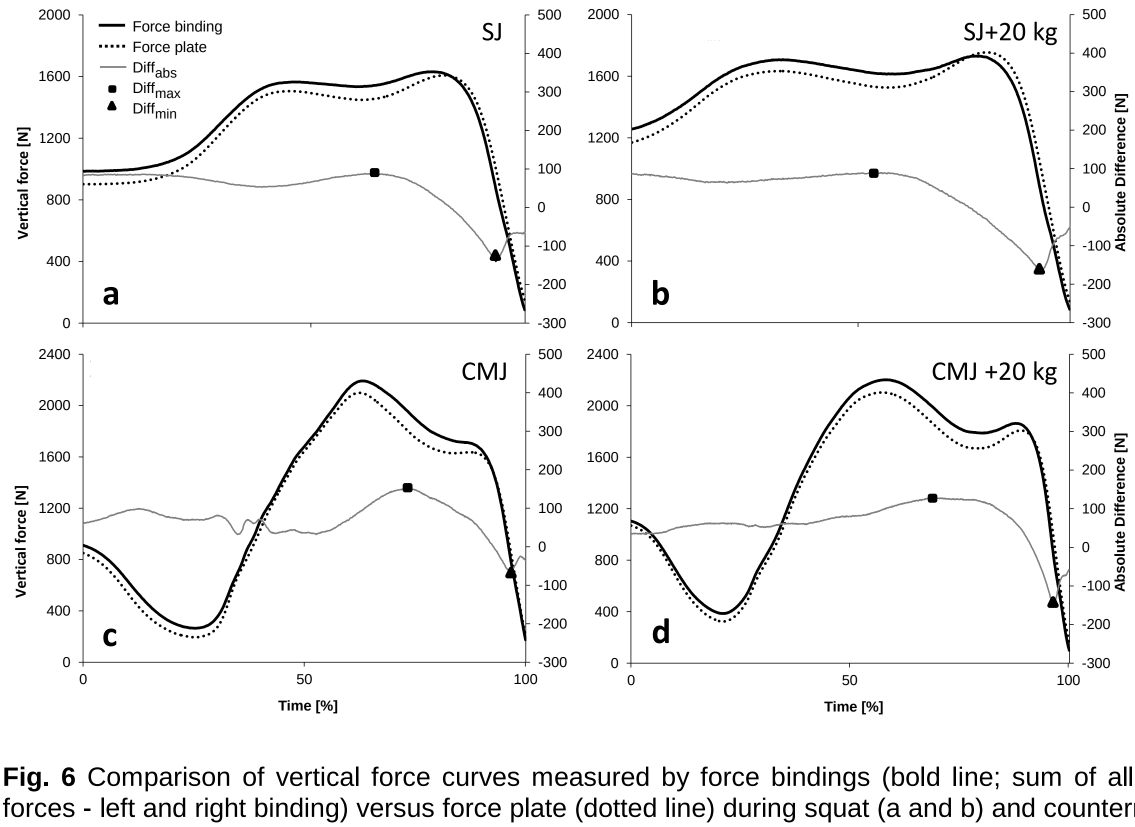

Fig. 6 Comparison of vertical force curves measured by force bindings (bold line; sum of all vertical part forces - left and right binding) versus force plate (dotted line) during squat (a and b) and countermovement (c and d) jumps with (b and d) and without (a and c) 20 kg extra weight. Absolute differences over time are demonstrated (grey line)

The landing situation during CMJ caused extremely high peak forces (over 5000 N), which were approx. fourfold compared to forces recorded during skate cross-country skiing at maximum velocity [17,26,10,21]. Nevertheless, the differences between the force plate and the force binding were approx. -8 % at the peak force and only approx. 0.5 % for the impulse of force during the landing situation. Both of these results appear to be low for such extreme loads suggesting that even higher loads do not negatively affect due to the robust construction of the binding.

DJs and SkJs were more specific imitation jumps for cross-country skiing that simulate diagonal and skating push-off phases. These jumps were performed on the force plate using only one leg with the classic or skate binding attached to a ski. Results of the DJ and SkJ are shown in Table 3. The greatest differences during skiing imitation jumps were recorded during diagonal jumps (Figure 7). Differences in peak forces were approx. 10 % to 15 % for the vertical and approx. 18 % for the anterior-posterior force components. For the vertical components forces were slightly overvalued around the highest forces (Figure 7 a and b) and for the anterior-posterior force component during the whole jump (Figure 7 c and d). This indicated that a more natural movement, where the center of pressure is moving along the force binding (simulating the diagonal stride push-off) is causing an error in the vertical direction during push-off discussed in detail when comparing the errors of both bindings. This effect is smaller in the direction along the ski/binding, however there was a constant absolute error during the push-off phase probably due to a cross-talk effect. These differences also caused higher impulses of force with the force binding in vertical (approx. 10 %) and anterior-posterior (approx. 20 %) force components.

Table 3 Comparison of force variables between the cross-country skiing specific force bindings and a standard force plate during imitation jumps for diagonal skiing and skating technique without and with 20 kg extra weight

Variables	Condition			
	FB	FP	$Diff_{abs}$ (N)	$Diff_{rel}$ (%)
DJ				
F_{Z_peak} (N)				
+0 kg	1,393 ± 115	1,257 ± 99	136 ± 21	10.8 ± 1.2
+20 kg	1,857 ± 125	1,614 ± 89	243 ± 40	14.9 ± 1.8
I_{Fz} (Ns)				
+0 kg	592 ± 40	548 ± 41	43 ± 6	8.0 ± 1.3
+20 kg	720 ± 56	652 ± 60	68 ± 6	10.5 ± 1.7
F_{Y_peak} (N)				
+0 kg	378 ± 64	321 ± 58	57 ± 12	18.1 ± 4
+20 kg	539 ± 53	459 ± 50	80 ± 12	17.7 ± 3.1
I_{Fy} (Ns)				
+0 kg	145 ± 14	121 ± 13	24 ± 2	19.9 ± 2.1
+20 kg	189 ± 13	162 ± 12	27 ± 4	16.9 ± 2.4
SkJ				
F_{Z_peak} (N)				
+0 kg	1,622 ± 117	1,536 ± 74	85 ± 69	5.5 ± 4.5
+20 kg	1,732 ± 123	1,714 ± 91	18 ± 82	1.1 ± 4.7
I_{Fz} (Ns)				
+0 kg	629 ± 30	615 ± 43	13 ± 37	2.4 ± 5.9
+20 kg	730 ± 59	718 ± 65	12 ± 22	1.8 ± 3.3
F_{X_peak} (N)				
+0 kg	528 ± 112	545 ± 51	−17 ± 67	−3.8 ± 11.4
+20 kg	496 ± 44	515 ± 28	−20 ± 25	−3.9 ± 4.8
I_{Fx} (Ns)				
+0 kg	159 ± 26	169 ± 11	−10 ± 21	−5.9 ± 12
+20 kg	163 ± 30	172 ± 15	−9 ± 20	−5.6 ± 11

Total binding forces in *z*, *y* or *x*-direction are calculated as sum of all part forces (front and rear sensors) of the corresponding binding (classic or skating binding) during push-off phase of the single-leg imitation jumps

Values are mean ± SD (10 repetitions per jump mode and condition)

FB force binding, *FP* force plate, $Diff_{abs}$ absolute difference between systems, $Diff_{rel}$ relative difference between systems, *DJ* single-leg diagonal imitation jump, *SkJ* single-leg skating imitation jump, $F_{Z/Y/X\_peak}$ vertical/anterior–posterior/medio-lateral peak force, $I_{Fz/y/x}$ impulse of vertical/anterior–posterior/medio-lateral force

Differences in SkJ using the skate binding were less than half compared to DJ using the classic binding. Regarding peak vertical forces, differences between force plate and the skate binding were 5.5 % or less and peak medio-lateral forces -3.9 % or less. In addition, the differences between the force measurement systems varied within the jump (Figure 8 a to d), which also resulted in small differences in impulses of force (vertical: approx. 2 %; medio-lateral: approx. -6 %). The results from the skate binding can be considered as promising and acceptable for highly dynamic situations, especially since these values were calculated using angular data from a high-speed camera to transform the forces into the same coordinate system as the force plate.

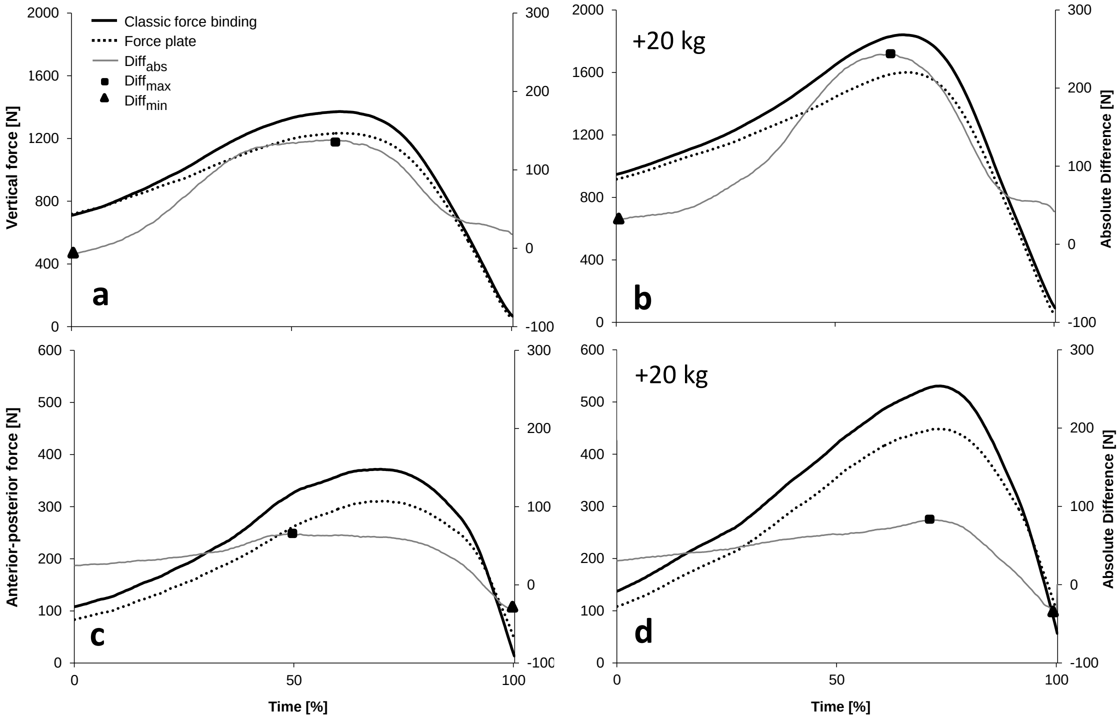

Fig. 7 Comparison of vertical (a and b) and anterior-posterior (c and d) force curves measured using the classic binding (bold line; sum of corresponding front and rear part forces) versus the force plate (dotted line) during diagonal imitation jumps with (b and d) and without (a and c) 20 kg extra weight. Absolute differences over time are demonstrated (grey line)

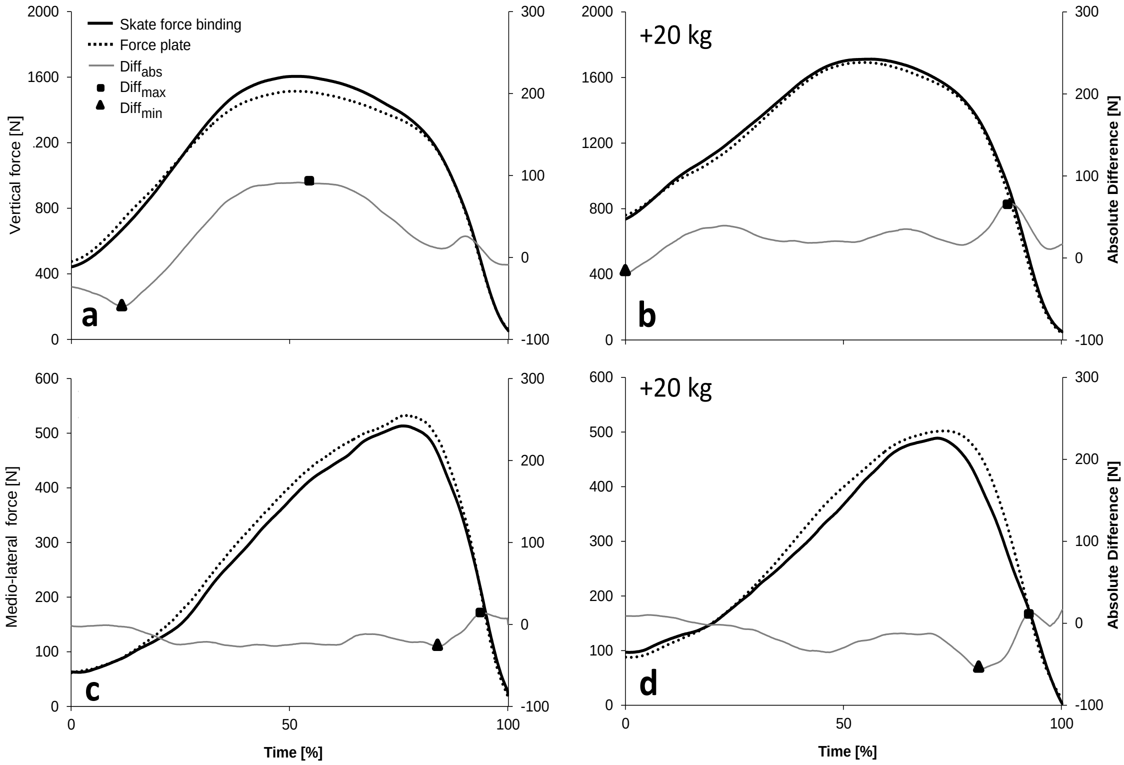

Fig. 8 Comparison of vertical (a and b) and medio-lateral (c and d) force curves measured by the skate binding (bold line; sum of corresponding front and rear part forces) versus force plate (dotted line) during skating imitation jumps with (b and d) and without (a and c) 20 kg extra weight. Absolute differences over time are demonstrated (grey line)

The smaller differences observed in the skate binding compared to the classic binding may have occurred due to the different constructions and designs of the two bindings as well as the mechanically different movements and mechanical stresses acting on the bindings during these specific jumps. During DJ push-off the center of pressure is moving forward along the force binding and the maximum force is produced when the subject's heel is lifted from the rear plate of the force binding. This might create a moment acting on the front part of the classic binding, which possibly causes a greater error. During SkJ the push-off force is almost perpendicular to the skate binding and the acting angle of force in relation to the force binding is not changing as much as during DJ, which might cause less moments.

Mean absolute differences between the force plate and the force binding for vertical force components (Table 4) were lower for SkJ (approx. 27 N to 50 N) and higher for DJ (77 N to 125 N) when compared to SJ (71 N to 74 N) and CMJ (76 N to 77 N). These results support the suggestion that the vertical force sensors of the classic binding measured forces too high. This can be seen in the higher differences compared to the force plate during DJ, which were performed only with the classic binding. Mean differences were smaller during SJ and CMJ compared to DJ, which is probably caused by the use of both bindings and the summing of the force signals during SJ and CMJ, which presumably reduced the error of these jumps. The smallest mean differences were observed during SkJ, which were performed only using the skate binding. These results highlight the different behavior of these two bindings during sport-specific movements.

Table 4 Similarity coefficients and differences between time normalized force curves recorded by different measurement systems during various jump and imitation exercises (with and without 20 kg extra weight) in laboratory conditions and during diagonal and skating skiing on snow

Force curves	Condition		
	SC	$Diff_{abs}$ (N)	$Diff_{rel}$ (%)
FB versus FP			
F_{Z_SJ}			
+0 kg	0.9859	71 ± 22 (−132 to 88)	5.5 ± 2.3 (−7.8 to 9.5)
+20 kg	0.9824	74 ± 28 (−164 to 90)	4.6 ± 2.0 (−13.9 to 6.3)
F_{Z_CMJ}			
+0 kg	0.9978	76 ± 34 (−67 to 151)	12.1 ± 11.6 (0.9 to 36.9)
+20 kg	0.9971	77 ± 31 (−145 to 128)	7.5 ± 4.4 (1.2 to 19.8)
F_{Z_DJ}			
+0 kg	0.9958	77 ± 49 (−10 to 143)	8.2 ± 3.3 (0.2 to 11.3)
+20 kg	0.9943	125 ± 76 (30 to 248)	10.3 ± 4.0 (1.8 to 15.4)
F_{Y_DJ}			
+0 kg	0.9901	44 ± 17 (−34 to 68)	21.7 ± 3.9 (7.0 to 27.4)
+20 kg	0.9921	52 ± 20 (−37 to 85)	18.7 ± 3.7 (5.1 to 25.7)
F_{Z_SkJ}			
+0 kg	0.9979	50 ± 29 (−61 to 93)	4.2 ± 2.1 (−13.6 to 6.0)
+20 kg	0.9994	27 ± 13 (−27 to 69)	2.3 ± 1.7 (−14.9 to 10.3)
F_{X_SkJ}			
+0 kg	0.9986	17 ± 9 (−29 to 15)	6.0 ± 3.1 (−7.6 to −1.1)
+20 kg	0.9961	19 ± 15 (−57 to 16)	5.9 ± 3.9 (0.5 to 9.3)
FB versus FP_tunnel			
F_{Z_DIAG}			
Skiing	0.9934	58 ± 51 (−85 to 244)	7.3 ± 4.1 (2.4 to 18.9)
F_{Y_DIAG}			
Skiing	0.9787	17 ± 8 (−3 to 40)	12.1 ± 8.5 (−10.0 to 37.5)
FB versus insoles			
F_{Z_SKATE}			
Skiing	0.9884	93 ± 52 (−78 to 194)	13.0 ± 5.0 (4.8 to 26.3)

Total binding forces in *z*, *y* or *x*-direction are calculated as sum of all part forces (front and rear sensors) of the corresponding binding (classic or skating binding). The range of similarity coefficients (SC) is $-1 <$ similarity < 1, where -1 means entirely contrary time histories, 0 means no similarity and 1 means high similarity. Difference values are mean ± SD (range min–max) calculated over the whole force curve (10 repetitions per mode and condition)

FB force binding, *FP* force plate, *FP_tunnel* long force platform in the ski tunnel, $Diff_{abs}$ absolute difference between systems, $Diff_{rel}$ relative difference between systems, *SJ* squat jump, *CMJ* countermovement jump, *DJ* single-leg diagonal imitation jump, *SkJ* single-leg skating imitation jump, *DIAG* diagonal skiing, *SKATE* skating technique, $F_{Z/Y/X}$ vertical/anterior–posterior/medio-lateral forces during different movement modes

Generally observing, all laboratory imitation jumps (SJ, CMJ, DJ and SkJ) showed high similarity coefficients (Table 4) in all situations with the lowest value of 0.982 from SJ with 20 kg extra load to the highest value of 0.999 from the vertical force component of SkJ with 20 kg extra load. This suggests a nice force curve reproduction in terms of specificity of different sport specific tasks, a fact that may get essential when comparing inter-individual technique strategies during push-off and gliding phases in cross-country skiing techniques.

3.3 Comparison measurements during diagonal skiing and skating on snow

The mean differences between the long force platform and classic binding (Figure 9 a and b) during diagonal stride over a total ground contact phase were 58 N and approx. 7 % for the vertical force component and 17 N and approx. 12 % for the anterior-posterior force component. These results are quite well in line with differences in DJ (77 N and 7.5 % for the vertical and 44 N and 21.7 % for the anterior-posterior component). The results of the skiing comparisons are presented in Table 4. There may be several reasons which might cause uncertainty in these results, for example a slight ski edging during diagonal skiing over the force platform, which could not be controlled but may have caused shifts between the coordinate systems of the force binding and the long force platform. Therefore, these results can be considered as only indicative.

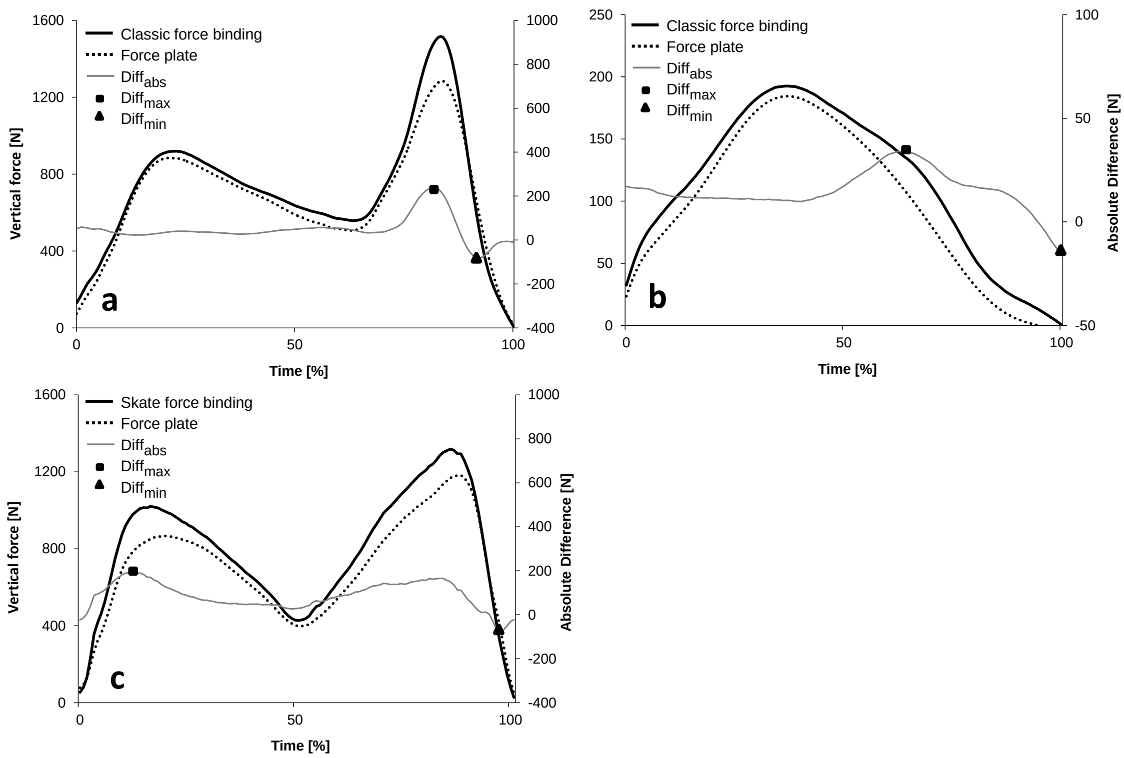

Fig. 9 Comparison of vertical (a) and longitudinal (b) force curves measured by the classic force binding (bold line; sum of corresponding front and rear part forces) versus the long force platform mounted in snow (dotted line) during classic skiing in the ski tunnel, and comparison of vertical (c) force curves measured by skate binding versus Pedar pressure insoles during skating on snow. Absolute differences over time are demonstrated (grey line)

During skate skiing, the mean difference between Pedar insoles and the skate binding over ground contact was 93 N and 13.0 % for the vertical force component. Lindinger 2005 [15] and other studies [14,27] reported lower values measured by the Pedar system compared to other standard force plates with values of -1,5 % to -6 % at peak values during skating push-offs and up to -14% in other phases of the ground contact. Interestingly and in contrast to the study of Lindinger 2005 [15], results of the current study showed that the highest differences between systems were recorded during maximum force (Figure 9 c) which may also indicate that the skate binding may measure slightly too high values due to unknown mechanical reasons. In studies of other winter sports, e.g. alpine skiing [28,29], Pedar insoles have also been reported to show lower values compared to other systems.

Despite these limitations we again observed high similarity coefficients when comparing with both reference systems during skiing on snow (classic: vertical 0.993, anterior-posterior 0.979; skating: vertical 0.988) which supports the assumption that the force bindings are valid and reliable also in field conditions. Similarity coefficients have been also used elsewhere when comparing force measurement systems. For example Stricker et al. [28] reported similarity coefficients ranging from 0.974 to 0.977 between custom made 3D dynamometer and Pedar pressure insoles during alpine skiing.

Overall, when examining the mean differences (Table 4) in all situations, the greatest differences between the force binding and any used reference system were observed in the classic binding during DJ situations (approx. 20 %). Much lower differences were found from skiing (skate: vertical 13 %; diagonal: anterior-posterior 12.1 %) as well as in CMJ (12.1 %; with 20 kg extra load) and SJ (10.3 %; with 20 kg extra load). All other differences were less than 10 %. Mean differences during SkJ using the skate binding were 6 % or less for both measured force components and load situations.

4 Conclusion

In summary, it can be concluded that through all steps of the validation process there was a difference in the functionality between classic and skate binding constructions. Sensor tests in our laboratory showed high linearity for both bindings, while repeatability tests indicated small differences between pre and post-tests in both laboratory and ski tunnel measurements. Mechanical stress caused by one hour of skiing showed some effects on the classic binding sensors. Greater differences were observed for the classic binding compared to the skate binding in comparison to the force plate when performing different modes of jumps with less accuracy observed during DJ at higher forces. The comparison of the force binding to a reference system during on snow skiing showed high similarity correlations for both classic and skate bindings, indicating a high validation level in terms of specific reconstruction of the task specific ground reaction forces in several relevant force components. The lower accuracy of the classic binding compared to the skating binding are most likely due to different mechanical properties caused by the construction and making the binding more sensitive for measurement errors especially during diagonal imitation type jumps. Further improvements are therefore needed for the classic binding. The most crucial point will be to prolong the front part of the classic binding. This would enable the pressure of the body to be distributed over a longer portion of the binding during the push-off phase and therefore causing a lower moment. In addition, the placements of the strain gauges need to be re-considered. These points are taken into account in the planning of the next version of the classic binding. The skate binding, on the other hand, was shown to be reliable during all measurements from sensor tests to more applied jumping tests and skiing on snow. Based on these results, the skate binding was shown to be valid and reliable for use in cross-country skiing skate technique measurements with differences of 6 % or less in all tested situations.

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Conflict of interest

The authors have no financial relationship with the organization that sponsored the research. The authors declare that they have no conflict of interest.

References

1. Ekström H (1981) Force interplay in cross-country skiing. Scandinavian Journal of Sports Science 3 (3):69-76
2. Komi PV (1987) Force Measurements during Cross-Country Skiing. Int J Sport Biomech 3 (4):370-381
3. Leppavuori AP (1989) Lihasaktiivisuus ja voimankäyttö maastohiihdossa. Muscle activity and force production in cross-country skiing. Master thesis, Univesity of Jyväskylä,
4. Pierce JC, Pope MH, Renström P, Johnson RJ, Dufek J, Dillman C (1987) Force measurement in cross-country skiing. Int J Sport Biomech 3 (4):382-391
5. Street GM, Frederick EC (1995) Measurement of Skier-Generated Forces During Roller-Ski Skating J Applied Biomechanics 11 (3):245-256
6. Babiel S (2003) Studies on intra-individual variability of selected cross-country skiing techniques. European Journal of Sport Science 3 (3):1-10. doi:10.1080/17461390300073305
7. Babiel S, Hartmann U, Spitzenpfeil P, Mester J (1997) Ground-reaction forces in alpine skiing, cross-country skiing and ski jumping. In: Müller E, Schwameder H, Kornexl E, Raschner C (eds) Science and skiing. pp 200-207
8. Babiel S, Neumaier A (2001) Studies on intra- and inter-individual variability of selected cross-country skiing techniques. In: Muller E, Schwameder H, Raschner C, Lindinger S, Kornexl E (eds) Science and Skiing II pp 299-306
9. Linnamo V, Ohtonen O, Stöggl T, Komi P, Müller E, Lindinger S (2012) Multi-dimensional Force Measurement Binding Used During Skating in Cross-Country Skiing. In: Müller E, Lindinger S, Stöggl T (eds) Science and Skiing V. pp 540-548
10. Ohtonen O, Lindinger S, Linnamo V (2013) Effects of gliding properties of cross-country skis on the force production during skating technique in elite cross-country skiers. International Journal of Sports Science & Coaching 8 (2):407-416. doi:10.1260/1747-9541.8.2.407
11. Bellizzi MJ, King KA, Cushman SK, Weyand PG (1998) Does the application of ground force set the energetic cost of cross-country skiing? Journal of applied physiology 85 (5):1736-1743
12. Hoset M, Rognstad AB, Rölvag T, Ettema G, Sandbakk Ö (2013) Construction of an instrumented roller ski and validation of three-dimensional forces in the skating technique. Sports Eng. doi:10.1007/s12283-013-0130-2
13. Smith G, Kvamme B, Jakobsen V (2009) Effectiveness of ski and pole forces in ski skating. In: Müller E, Lindinger S, Stöggl T (eds) Science and Skiing IV - Congress proceedings - 4th International congress on science and skiing (ICSS 2007). Meyer & Meyer Sport, UK, pp 647-656
14. Holmberg HC, Lindinger S, Stoggl T, Eitzlmair E, Muller E (2005) Biomechanical analysis of double poling in elite cross-country skiers. Medicine and Science in Sports and Exercise 37 (5):807-818. doi:10.1249/01.mss.0000162615.47763.c8
15. Lindinger S (2005) Biomechanische Analysen von Skatingtechniken im Skilanglauf (Biomechanical analysis of skating techniques in cross-country skiing). Spektrum Bewegungswissenschaft, vol Bd. 4. Meyer & Meyer Sport, Aachen, Germany
16. Lindinger SJ, Stoggl T, Muller E, Holmberg HC (2009) Control of speed during the double poling technique performed by elite cross-country skiers. Medicine and Science in Sports and Exercise 41 (1):210-220. doi:10.1249/MSS.0b013e318184f436
17. Stoggl T, Kampel W, Muller E, Lindinger S (2010) Double-push skating versus V2 and V1 skating on uphill terrain in cross-country skiing. Medicine and science in sports and exercise 42 (1):187-196. doi:10.1249/MSS.0b013e3181ac9748
18. Piirainen J (2008) Vuorohiihdon voimantuoton muutokset suksen pito-ominaisuuksia vaihtelemalla. Quality of grip waxing and the force production in classical skiing. Masters thesis, University of Jyväskylä,
19. Vahasoyrinki P (1996) Vuorohiihdon voimantuotto hiihtonousun kulman ja pito-ominaisuuksien vaihtuessa. Effect of track inclination and grip properties on the force production of diagonal skiing. Master thesis, University of Jyväskylä,
20. Vahasoyrinki P, Komi PV, Seppala S, Ishikawa M, Kolehmainen V, Salmi JA, Linnamo V (2008) Effect of skiing speed on ski and pole forces in cross-country skiing. Medicine and Science in Sports and Exercise 40 (6):1111-1116. doi:10.1249/MSS.0b013e3181666a88
21. Leppavuori AP, Karras M, Rusko H, Viitasalo JT (1993) A New Method of Measuring 3-D Ground Reaction Forces under the Ski during Skiing on Snow. J Appl Biomech 9 (4):315-328

22. Smith GA (2003) Biomechanics of cross country skiing. In: Rusko H (ed) Handbook of Sports Medicine and Science - Cross Country Skiing. Blackwell Science Ltd., p 46
23. Mero A, Kuitunen S, Harland M, Kyröläinen H, Komi PV (2006) Effects of muscle – tendon length on joint moment and power during sprint starts. Journal of Sports Sciences 24 (2):165-173
24. Bates BT (1996) Single-subject methodology: an alternative approach. Medicine and science in sports and exercise 28 (5):631-638
25. Birklbauer J (2006) Azyklische Bewegungen. In: Birklbauer J (ed) Modelle der Motorik (Models of motor control and learning). Meyer & Meyer Verlag, Aachen, pp 292-318
26. Stoggl T, Muller E, Lindinger S (2008) Biomechanical comparison of the double-push technique and the conventional skate skiing technique in cross-country sprint skiing. Journal of sports sciences 26 (11):1225-1233. doi:10.1080/02640410802027386
27. Lindinger SJ, Gopfert C, Stoggl T, Muller E, Holmberg HC (2009) Biomechanical pole and leg characteristics during uphill diagonal roller skiing. Sports biomechanics / International Society of Biomechanics in Sports 8 (4):318-333. doi:10.1080/14763140903414417
28. Stricker G, Scheiber P, Lindenhofer E, Müller E (2009) Determination of forces in alpine skiing and snowboarding: Validation of a mobile data acquisition system. European Journal of Sport Science 10 (1):31-41. doi:10.1080/17461390903108141
29. Nakazato K, Scheiber P, Müller E (2011) A comparison of ground reaction forces determined by portable force-plate and pressure-insole systems in alpine skiing. Journal of Sports Science and Medicine 10:754 - 762