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Relationships between biomechanics and physiology in older, recreational alpine skiers

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The aims of this applied field study were (1) to provide descriptive data on the biomechanical variables of *parallel ski steering*, *carving in long radii* and *individual technique* skiing modes of older recreational skiers and (2) to determine the relationships between biomechanical and physiological variables during these skiing modes. The mean knee angle (MKA), range of knee angle (RKA), ground reaction forces (GRF), co-loading of the inner leg, mean heart rate (HR_{ave}), blood lactate (LA) and mean arterial pressure were determined for 14 older skiers (61.1 ± 5.4 years). The mean GRF did not differ between the skiing modes. *Parallel ski steering* resulted in a greater MKA, lower RKA and lower peak GRF compared with *carving in long radii* and *individual technique*. LA correlated positively to RKA during *carving in long radii* and *individual technique*, while HR_{ave} correlated negatively to MKA during *parallel ski steering* and *carving in long radii*. No significant relationships were found between the physiological and kinetic variables. In conclusion, dynamic skiing styles may result in increased muscle fiber recruitments, hence greater LA levels. Along with potentially greater loading of knee extensor muscles, lower MKAs may reduce perfusion and hinder substrate metabolism, consequently making ski turning more strenuous. Skiing with less knee flexion and a reduced RKAs could be recommended for older recreational skiers.

Biomechanical parameters exert a substantial influence on the physiological response during exercise (Martin & Morgan, 1992). Complex movement exercises are characterized by many varying kinematic and kinetic parameters. Consequently, the influence of biomechanical parameters on the physiological response during these exercises is a complicated issue (Williams & Cavanagh, 1987; Kyröläinen et al., 1995). Recreational alpine skiing is an exercise with many varying factors, such as slope conditions, skiing speed, turn radii and individual skiing styles (Seifert et al., 2009). Previous investigations demonstrated that individual skiing style, and not fitness level, plays an important role in the physiologic response of older recreational skiers (Scheiber et al., 2009b, 2010). Physical capacities of older people are reduced due to the aging process (Brooks & Faulkner, 1994; Thompson, 1994; Mattern et al., 2003). Consequently, the changes in skiing conditions and skiing styles significantly affect the physiological response of older skiers (Scheiber et al., 2009b). Physiological responses, but not biomechanical characteristics of older recreational skiers, have been described previously (Karlsson et al., 1978; Krautgasser et al., 2009; Scheiber et al., 2009a, b, 2010). It is unknown, however; to what extent the physiological responses of older recreational skiers are influenced by the biomechanical variables of their skiing styles. Detailed knowledge of these relationships demonstrates a benefit for scientists working in the specific field of exercise science, as well as for ski instructors in their daily work.

Ski instructors mostly pace their clients by using the skiing modes of *parallel ski steering* for low-intensity ski runs and *carving in long radii* for high-intensity ski runs (Wörndle et al., 2007). The Austrian Ski Teaching Concept characterizes the traditional skiing mode of *parallel ski steering* by skidded turns, while turns during *carving in long radii* skiing mode are carved with less skidded phases. In addition to these paced skiing modes, skiers perform their *individual technique* for self-paced runs. The *individual technique* skiing mode is not related to the recommendations of the Austrian Ski Teaching Concept and may result in a large inter-personal variation. The first aim of this study was to provide descriptive data of kinematic and kinetic variables and to quantify differences in these variables of older, recreational skiers during *parallel ski steering*, *carving in long radii* and *individual technique* skiing modes.

Based on the Austrian Ski Teaching Concept, we hypothesized that *parallel ski steering* skiing modes result in a higher skiing position [greater mean knee angle (MKA)] than *carving in long radii* skiing modes. Additionally, we expected to find a greater vertical movement [greater range of knee angle (RKA)] for *parallel ski steering*, compared with *carving in long radii* skiing modes. From a kinetic point of view, we assumed that greater ground reaction forces (GRF), combined with an increased co-loading of the inner leg, would occur during *carving in long radii* skiing modes, compared with *parallel ski steering* skiing. The question then arises whether kinematic and kinetic variables of the *individual technique* skiing mode are more similar to those of *carving in long radii* or to *parallel ski steering*.

Alpine skiing is an activity that is characterized by a mixture of dynamic and static muscle work (Nygaard et al., 1978; Tesch, 1995; Müller & Schwameder, 2003; Kröll et al., 2010). Dynamic exercise may lead to an increased muscle activity and consequently to an increased physiological response (Lewis et al., 1985; Gollnick et al., 1986; Kayser et al., 1994). Depending on the skiing mode, skiing style and skiing terrain, the skier may be in a more upright or in a more tucked position (Wörndle et al., 2007), which may also influence the physiological responses of skiers. Increased physiological responses and hemoglobin desaturation were found in low-position vs high-position speed skating (Rundell, 1996; Rundell et al., 1997; Foster et al., 1999), during slide boarding (Leirdal et al., 2006) and alpine skiing (Szmedra et al., 2001). From a kinetic point of view, high GRF are acting upon the skier during skiing (Babiel et al., 1997; Müller & Schwameder, 2003; Spitzenpfeil et al., 2009). These GRF are mainly determined by speed and turn radii. Generally, increasing external loads result in an increased muscle activity (Kyröläinen et al., 2005) and may lead to higher physiological demands during exercise. The second aim of the study was to correlate kinematic and kinetic variables during *parallel ski steering*, *carving in long radii* and *individual technique* skiing modes with the physiological variables during these trials. We hypothesized that the RKA correlates positively and the MKA correlates negatively with the physiologic response in skiing. Additionally, we expected a positive relationship between GRF and the physiological response.

Materials and methods

Participants and general test design

Fourteen experienced, older (61.1 ± 5.4 years) recreational skiers (Table 1) volunteered to participate in this study. The study was approved by the local ethics committee. Before all the tests, subjects were informed of the nature, risk and benefit of the investigation, and a written consent was obtained. Based on the Austrian Ski Teaching Concept (Wörndle et al., 2007), subject's skiing skills were on the high end of the intermediate level. Intermediate-level skiers are able to perform short and long radii turns on flat and steep slopes. They are also able to perform controlled ski runs on unprepared terrain. All participants were experienced in skiing for >40 years. Tests took place at the ski area of Abtenau, Salzburg, Austria, on a daily groomed and homogenous slope, with an average inclination of 17°. The length of the test run was ~ 1,300 m, and the altitude was between 746 and 954 m. The testing period extended over 2 weeks in March. Skiing trials were only accomplished in the morning hours as to provide consistent conditions. Twenty-five double turns were performed by each subject for *parallel ski steering*, *carving in long radii* and *individual technique* skiing mode. The *parallel ski steering* and *carving in long radii* skiing modes were paced by a certified ski instructor to ensure the consistency of speed and turn radii for all subjects. The ski instructor demonstrated the skiing modes in accordance with the principles of the Austrian Ski Teaching Concept (Wörndle et al., 2007). Each skier was instructed to follow the ski instructor's track and to maintain the given pace. During *individual technique* skiing modes, the participants were asked to ski with a constant pace and in accordance to their individual skiing style.

Table 1. Subjects' physical characteristics

Variable	Mean ± SD (minimum–maximum)
Age (years)	61.1 ± 5.4 (53–70)
Height (cm)	171.3 ± 8.4 (154–183)
Weight (kg)	72.1 ± 11.5 (51–87)
BMI	24.4 ± 2.1 (20.9–28.6)

BMI, body mass index.

Characterization of skiing modes

The traditional skiing mode of *parallel ski steering* is characterized by skidded turns (Müller & Schwameder, 2003; Wörndle et al., 2007). During the initial phase of the turn, a distinctive upward movement of the center of mass (up-unloading) is necessary to transfer weight from one ski to the other. This is typically executed by extending the legs through an increase in ankle-, knee- and hip-joint angles. After passing the fall line, the position of center of mass is continuously lowered until the end of the turn. Additionally, the *parallel ski steering* skiing mode is characterized by a definitive greater loading of the outer leg compared with the inner leg. Ski turns during the *carving in long radii* skiing mode are carved with less skidded phases. *Carving in long radii* is characterized by a higher speed compared with *parallel ski steering*. Even though it is not as distinctive as what is observed in *parallel ski steering*, up-unloading is also typical for the *carving in long radii* skiing mode (Wörndle et al., 2007). The load of the outer leg is still greater than the load of the inner leg, but an increased co-loading of the inner leg is typical for this skiing mode. Because the *individual technique* skiing mode is a personal skiing style, descriptive data are not published.

Data collection

Heart Rate and run times were measured continuously during skiing, using a mobile heart rate monitor (t6, Suunto, Helsinki, Finland), to assess the mean heart rate (HR_{ave}). Immediately after each ski run, systolic and diastolic blood pressures were measured (Omron BP Cuff, RX Classic, Mannheim, Germany) and the mean arterial pressure (MAP) was calculated from these values. One minute after the completion of each ski run, blood lactate (LA) was collected from an earlobe blood sample (EKF, Biosen 5040, Magdeburg, Germany).

The knee angle was measured unilaterally and continuously during the three skiing modes with a sample rate of 500 Hz, using a goniometer (Biovision, Wehrheim, Germany). The goniometer was fixed via tape and calibrated at 90° and 180° before and after the runs. The kinematic data were stored on an iPAQ 3800 PDA (Hewlett-Packard, Palo Alto, California, USA) placed in the backpack of the skier.

Based on a pilot study, before the data collection, pressure insoles (Novel, Munich, Germany) were used to determine the kinetic data instead of three-dimensional force plates. Insoles have the advantage wherein they do not influence skiers' technique substantially and the skiers can use their own equipment. The GRF were measured unilaterally at a sample rate of 50 Hz and stored on a data logger, placed in the backpack of the skier. Different insole sizes, varying from 244 to 272 mm insole length, were used to ensure proper fitting for each subject. All insoles were pre-calibrated in the laboratory, in accordance to the calibration guidelines of Novel. Before each test run, the insoles were unloaded for baseline settings.

All trials were filmed and documented via a digital camcorder (50 Hz) to determine turn phases, edge changing, and to estimate vertical and horizontal distances and turn radii of the double turn. Therefore, the width and length of the slope were determined using a geodetically system and defined landmarks. The trajectory for each skiing mode was calculated using the following equation(Kagawa & Yoneyama, 2001):

$$f(x) = (\text{horizontal distance}) \sin[(\text{vertical distance})x] \quad (1)$$

The length of the skiing trajectory was calculated using the following equation:

$$L = \Sigma\sqrt{(\text{horizontal distance}_{(i)}^2 + \text{vertical distance}_{(i)}^2)} \quad (2)$$

The video, the kinematic data and the kinetic data were synchronized by a jump at the start of each run. After this jump, skiers performed 25 double turns for each skiing mode, followed by another jump at the end of the run.

Data analysis

A double turn was defined as one right turn, followed by a left turn. Edge changing between the right and the left turn was used as a criterion to separate the turns. The first three and the last two double turns were not included. Twenty double turns were analyzed for each skier and each skiing mode. Therefore, the raw data of 20 double turns of each skier were time normalized and the mean (± SD) time characteristics were calculated. The MKA was calculated for the inner (during the right turn) and the outer leg (during the left turn) and the vertical movement was determined by the RKA during the double turn. Total (inner+outer leg) GRFs were analyzed for mean (± SD) and peak values.

Statistical analysis

All data were checked for normality, using the Kolmogorov–Smirnov test, and presented as means and standard deviations (± SD) over all subjects. Maximal heart rate was estimated by 220 minus age (years). Kinetic data are presented as absolute values (*N*) and related to body weight (times of body weight). Repeated measures ANOVA was calculated for any changes in the physiological, kinematic and kinetic variables for *parallel ski steering*, *carving in long radii* and *individual technique* skiing modes. Greenhouse–Geisser adjustment of global significance was used when sphericity was not met. When global significances were found, *post hoc* analyses using Bonferroni's adjustments were further performed. Pearson's product–moment correlations and stepwise linear regressions were obtained to analyze the relationships among skiing speed, biomechanical and physiological data. Ikemaster 1.38 (Ike-Software Solutions, Salzburg, Austria), Office Excel 2007 (Microsoft Corporation, Redmond, Washington) and SPSS 16.0 (SPSS, Chicago, Illinois) were used for the statistical analysis. The level of significance was set *a priori* at $P<0.05$.

Results

A summary of all the descriptive results for the physiological, kinematic and kinetic data is displayed in Table 2. Figure 1 demonstrates the estimated trajectory and the estimated skiing speeds of the three skiing modes. The average run times of *parallel ski steering* (143 ± 14 s), *carving in long radii* (103 ± 7 s) and *individual technique* skiing modes (77 ± 12 s) were significantly different (all $P<0.001$). The estimated skiing speeds for *parallel ski steering* and *carving in long radii* were consistent for all subjects at ~ 28 and ~ 38 km/h, respectively. The skiing speed for the *individual technique* skiing mode varied between subjects, ranging from ~ 30 to 59 km/h. Only poor correlations were found between the skiing speed and any physiological variable.

Physiology

Similar to previous studies, the HR_{ave}, LA and MAP responses demonstrated a wide inter-personal range. The mean group LA levels were significantly different between all the skiing modes, all $P<0.01$ (Table 2). The *individual technique* skiing mode resulted in the highest LA concentration, while the *parallel ski steering* skiing mode demonstrated the lowest LA accumulation. Similar results were found for the HR_{ave} response (Table 2). The HR_{ave} for *parallel ski steering* (67 ± 10% of maximal heart rate) was significantly lower compared with *carving in long radii* (74 ± 11%) and *individual technique* (77 ± 10%) skiing, all $P<0.001$. No differences were found for MAP between skiing modes (Table 2).

Kinematics

Figure 2 demonstrates the mean unilateral time histories of the knee angle for the three skiing modes. During the right turn, each graph represented the inner leg, characterized by a continuously lowering of the knee angle. After a short plateau, the knee angle increased again and reached the maximum during the left turn, when the analyzed leg represented the outer leg, followed by another plateau.

Table 2. Mean ± SD (minimum–maximum) values of $n = 14$ subjects for lactate (LA), average heart rate (HR_{ave}), mean arterial pressure (MAP), mean knee angle of the inner (MKA_{in}) and outer (MKA_{out}) leg, range of knee angle (RKA), mean total (inside+outside leg) ground reaction forces ($GRF_{total,\ mean}$), peak total GRF ($GRF_{total,\ peak}$) and co-loading of the inner leg (Co-loading) for *parallel ski steering* (PSS), *carving in long radii* (CLR) and *individual technique* (IT) skiing modes. GRFs are related to body weight (BW)

	PSS	CLR	IT	$F_{(2,12)}$	P	η_p^2	Power
LA (mmol/L)	$1.30 \pm 0.26^{*\dagger}$ (0.93–1.70)	$1.75 \pm 0.56^{\dagger\ddagger}$ (0.87–2.98)	$2.14 \pm 0.81^{*\ddagger}$ (0.98–3.76)	18.03	0.00	0.58	1.00
HR_{ave} (b.p.m.)	$107 \pm 17^{*\dagger}$ (84–134)	$118 \pm 18^{*}$ (91–150)	$123 \pm 16^{*}$ (106–150)	36.98	0.00	0.74	1.00
MAP (mmHg)	109 ± 15 (93–134)	114 ± 14 (94–136)	107 ± 16 (90–136)	1.14	0.38	0.28	0.17
MKA_{in}	$118 \pm 6^{*\dagger}$ (108–129)	$111 \pm 6^{*}$ (96–121)	$112 \pm 7^{*}$ (100–126)	23.29	0.00	0.64	1.00
MKA_{out}	$131 \pm 7^{*\dagger}$ (117–142)	$126 \pm 6^{*}$ (117–137)	$125 \pm 6^{*}$ (116–135)	21.63	0.00	0.63	1.00
RKA	$24 \pm 5^{*\dagger}$ (16–34)	$28 \pm 5^{*}$ (21–41)	$26 \pm 6^{*}$ (18–35)	6.16	0.01	0.32	0.85
$GRF_{total,\ mean}$ (BW)	1.19 ± 0.22 (0.89–1.65)	1.25 ± 0.20 (0.93–1.55)	1.27 ± 0.20 (0.95–1.54)	4.31	0.02	0.25	0.70
$GRF_{total,\ peak}$ (BW)	$1.49 \pm 0.28^{*\dagger}$ (1.11–2.06)	$1.62 \pm 0.25^{*}$ (1.22–1.94)	$1.64 \pm 0.22^{*}$ (1.28–1.95)	8.55	0.00	0.4	0.95
Co-loading (%)	$35.6 \pm 4.2^{*\dagger}$ (28.4–41.3)	$32.5 \pm 4.3^{\dagger\ddagger}$ (26.6–36.8)	$38.8 \pm 4.4^{*\ddagger}$ (30.5–45.0)	27.91	0.00	0.68	1.00

Significant differences for all variables between skiing modes are indicated by:
*different from the CLR skiing mode, †different from the IT skiing mode, ‡different from the PSS skiing mode.

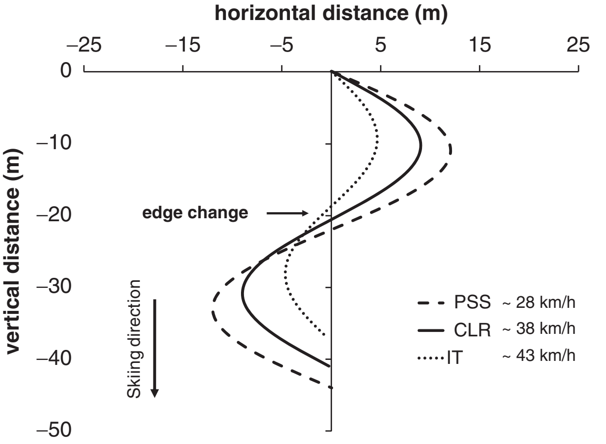

Fig. 1. Estimated trajectory $f(x)$ = (horizontal distance)sin [(vertical distance)x] of parallel ski steering (PSS), carving in long radii (CLR) and individual technique (IT) skiing modes.

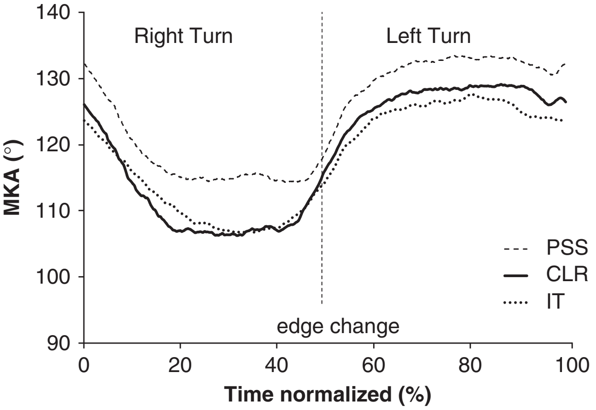

Fig. 2. Unilateral (right leg) time characteristics of the mean knee angle (MKA) of $n = 14$ subjects and 20 double turns for *parallel ski steering* (PSS), *carving in long radii* (CLR) and *individual technique* (IT) skiing modes. The average standard deviation was: 7.4° for PSS, 7.1° for CLR skiing modes and 7.3° for IT skiing modes. Data were time normalized before any calculation.

When comparing the three skiing modes, the greatest MKA (Table 2) was found for the *parallel ski steering* skiing mode for both the inner leg (118 ± 6°) and the outer leg (131 ± 7°), all $P < 0.01$. No differences were observed between *carving in long radii* and *individual technique* skiing modes. A smaller vertical movement (RKA) was found for the *parallel ski steering* skiing mode (24 ± 5°) compared with *carving in long radii* (28 ± 5°) and *individual technique* (26 ± 6°), all $P < 0.01$ (Table 2). Similar to the MKA, no differences were measured between *carving in long radii* and *individual technique* skiing modes for the RKA.

Kinetics

The mean unilateral time histories for the GRFs are shown in Fig. 3. During the right turn, which represented the inner leg, a definitive plateau was observed for the GRFs for all skiing modes. GRF for the outer leg increased during and after the edge changing. Table 2 lists the body weight-related mean and peak total GRF and the calculated co-loading of the inner leg compared with the outer leg. The mean total GRF did not differ for any skiing mode. The

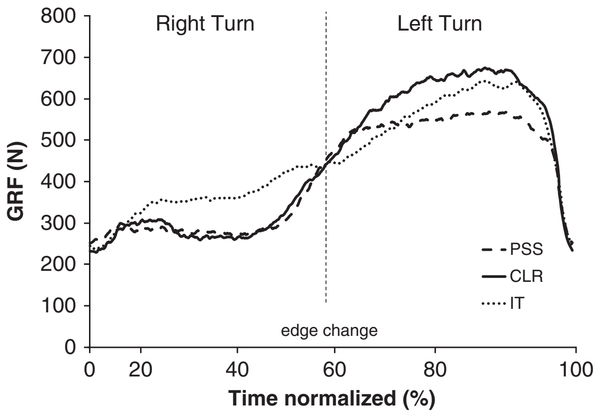

Fig. 3. Unilateral time characteristics (right leg) of ground reaction forces (GRF) of $n = 14$ subjects and 20 double turns for *parallel ski steering* (PSS), *carving in long radii* (CLR) and *individual technique* (IT) skiing modes. The average standard deviation was: 104 N for PSS, 120 N for CLR skiing modes and 122 N for IT skiing modes. Data were time normalized before any calculation.

parallel ski steering skiing mode resulted in a significantly lower peak total GRF compared with *carving in long radii* and *individual technique* skiing, all $P < 0.05$. Greater mean GRFs were measured on the inner leg during *individual technique* ($0.49 \pm 0.10 \times$ body weight), compared with *parallel ski steering* ($0.43 \pm 0.10 \times$ body weight) and *carving in long radii* ($0.41 \pm 0.10 \times$ body weight) skiing modes (all $P < 0.001$). Peak forces at the inner leg ranged from $0.61 \pm 0.12 \times$ body weight (*parallel ski steering*) to $0.67 \pm 0.13 \times$ body weight (*individual technique*) and did not differ significantly. In contrast, the outer leg was loaded significantly greater during the *carving in long radii* skiing mode ($0.84 \pm 0.13 \times$ body weight), compared with *parallel ski steering* ($0.77 \pm 0.15 \times$ body weight) and *individual technique* ($0.78 \pm 0.12 \times$ body weight) skiing (all $P < 0.05$). Peak forces at the outer leg ranged from $0.89 \pm 0.17 \times$ body weight (*parallel ski steering*) to $1.01 \pm 0.17 \times$ body weight (*carving in long radii*) and did not differ significantly. A greater co-loading of the inner leg was observed for the *parallel ski steering* skiing mode ($35.6 \pm 4.2°$) compared with the *carving in long radii* skiing mode ($32.5 \pm 4.3°$), $P < 0.01$. The *individual technique* skiing mode demonstrated the greatest co-loading ($P < 0.01$).

Table 3. Summary of relevant Pearson's product–moment correlation coefficients between the physiological, kinetic and kinematic variables of $n = 14$ subjects in *parallel ski steering* (PSS), *carving in long radii* (CLR) and *individual technique* (IT) skiing modes. Physiologic variables are blood lactate (LA), average heart rate (HR_{ave}) and mean arterial pressure (MAP). Kinematic variables are range of knee angle (RKA), mean knee angle of inner (MKA_{in}) and outer leg (MKA_{out}) during a double turn. Kinetic variables are mean ground reaction forces of the inner (GRF_{in} mean) and outer leg (GRF_{out} mean), peak ground reaction forces of the inner (GRF_{in}, peak) and outer leg (GRF_{out}, peak), total mean ($GRF_{total, mean}$) and total peak ($GRF_{total, peak}$) and the co-loading of the inner leg

	RKA	MKA_{in}	MKA_{out}	$GRF_{total, mean}$	$GRF_{total, peak}$
PSS					
LA	0.338	– 0.133	0.098	0.196	0.234
HR_{ave}	– 0.127	– 0.699**	– 0.617**	– 0.117	– 0.081
MAP	0.638	0.315	0.528	– 0.099	– 0.121
CLR					
LA	– 0.533*	– 0.255	0.020	0.424	0.440
HR_{ave}	– 0.213	– 0.557*	– 0.576*	– 0.199	– 0.108
MAP	0.301	0.559	0.606	– 0.140	– 0.385
IT					
LA	0.708**	– 0.118	0.11	0.248	0.348
HR_{ave}	0.019	– 0.496	– 0.421	– 0.249	– 0.263
MAP	0.155	0.225	0.369	0.073	– 0.056

$^*P < 0.05$; $^{**}P < 0.01$.

Relationships between biomechanics and physiology

Table 3 summarizes all relevant Pearson's product–moment correlation coefficients between the physiological and biomechanical variables. Stepwise multiple regression analysis of biomechanical variables (MKA, RKA, mean and total GRF) revealed the following prediction models for LA, HR_{ave} at the skiing modes of *parallel ski steering* (PSS), *carving in long radii* (CLR) and *individual technique* (IT) and are presented in Fig. 4(a)–(d):

$\mathrm{LA\ (CLR)} = 0.14 + 0.05 \cdot \mathrm{RKA}$; $R^2 = 0.224$; $P < 0.05$; $\mathrm{SEE} = 0.497$.

$\mathrm{LA\ (IT)} = -0.51 + 0.10 \cdot \mathrm{RKA}$; $R^2 = 0.502$; $P < 0.01$; $\mathrm{SEE} = 0.595$.

$HR_{ave}\ \mathrm{(PSS)} = 346.55 - 2.04 \cdot \mathrm{MKA}$ inner leg; $R^2 = 0.445$; $P < 0.01$; $\mathrm{SEE} = 12.693$.

$HR_{ave}\ \mathrm{(CLR)} = 337.59 - 1.74 \cdot \mathrm{MKA}$ outer leg; $R^2 = 0.276$; $P < 0.05$; $\mathrm{SEE} = 15.581$.

Stepwise multiple regression analysis excluded all biomechanical variables for LA (PSS), HR_{ave} (CLR), HR_{ave} (IT), MAP (PSS) and MAP (CLR).

Discussion

To our knowledge, the present study is the first to provide information on both the biomechanical and the physiological aspects of older recreational skiers during skiing. The main findings of the present study were: (1) the mean total GRF of *parallel ski steering*, *carving in long radii* and *individual technique* skiing modes did not differ, (2) the peak total GRF of the *parallel ski steering* skiing mode was significantly lower than that of *carving in long radii* and *individual technique* skiing modes, (3) *parallel ski steering* skiing mode resulted in a greater mean and lower range of the knee angle compared with *carving in long radii* and *individual technique* skiing modes, (4) LA was found to be significantly related to the RKA during

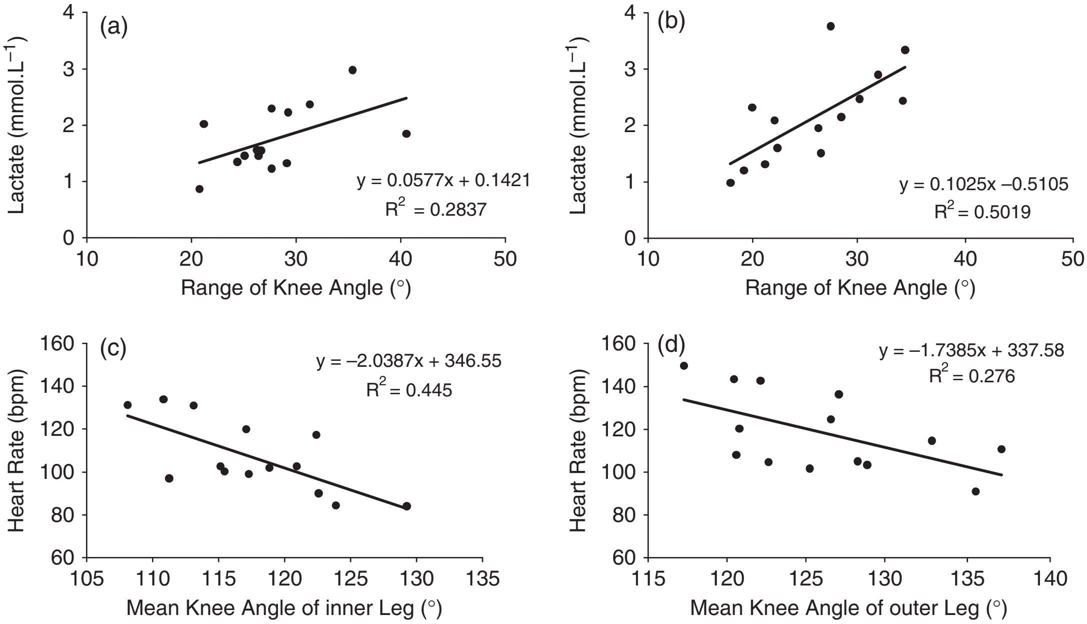

Fig. 4. (a) Relationship between blood lactate (LA) and range of knee angle (RKA) of $n = 14$ subjects and 20 double turns during the *carving in long radii* skiing mode ($P < 0.05$). (b) Relationship between LA and RKA of $n = 14$ subjects and 20 double turns during the *individual technique* skiing mode ($P < 0.05$). (c) Relationship between heart rate and mean knee angle (MKA) of the inner leg of $n = 14$ subjects and 20 double turns during the *parallel ski steering* skiing mode ($P < 0.05$). (d) Relationship between heart rate and MKA of the outer leg of $n = 14$ subjects and 20 double turns during the *carving in long radii* skiing mode ($P < 0.05$).

carving in long radii and *individual technique* skiing modes and (5) HR_{ave} demonstrated a significant relationship with the MKA during *parallel ski steering* and *carving in long radii* skiing modes.

From a kinematic perspective, a fast increase in the outer knee angle (from ~ 90° to ~ 120°) during the initial phase of the turn, followed by a plateau at 120–130° during the steering phase, was found for a skidded skiing mode by Müller and Schwameder (2003). For the inner leg, the knee angle decreased continuously from 120° to 95°. This skidded skiing mode was similar to the *parallel ski steering* skiing mode of the present study. Müller and Schwameder (2003) compared the results of the skidded skiing mode with a competition-carving ski mode and found similar results for the knee angle. However, this competition-carving skiing mode was not comparable with the *carving in long radii* skiing mode of the actual study due to technical differences. Consequently, data comparable to those of the present study do not exist for the *carving in long radii* skiing mode. For individual technique skiing modes, average knee angles of 94° (inner leg) and 114° (outer leg) were reported for intermediate-level skiers (Kröll et al., 2010). The results of the present study partly support, but are also in contrast to the earlier findings of Müller and Schwameder (2003), the recommendation of the Austrian Ski Teaching concept and our hypotheses: similar to the literature and our expectations, the *parallel ski steering* skiing mode resulted in a greater MKA of +7° for the inner leg and +4° for the outer leg compared with *carving in long radii* skiing mode. No differences in the MKA were found between *carving in long radii* and *individual technique* skiing modes. However, in contrast to our hypothesis, *parallel ski steering* skiing was the most static skiing mode (RKA = 24 ± 5°), while the *carving in long radii* skiing mode was characterized by greater knee extension (RKA = 28 ± 5°) that often accompanies a more pronounced vertical movement. Finally, the RKA of the *individual technique* skiing mode (RKA = 26 ± 6°) was between *parallel ski steering* and *carving in long radii* and demonstrates that – from a kinematic standpoint – the *individual technique* skiing mode was a mixture of *parallel ski steering* and *carving in long radii*. Lowering the center of mass results in a lower skiing position and is helpful for maintaining balance. The results of the present study demonstrate that older, recreational skiers use a distinctive knee extension combined with a potential vertical movement of the center of mass during the initial phase – so-called "up-unloading" – and lowering the center of mass during the steering phase, to perform a comfortable skiing mode.

From a kinetic point of view, alpine ski racing is defined as a sport discipline with a high GRF up to 7000 N acting on the athlete (Babiel et al., 1997; Spitzenpfeil et al., 2009). In contrast to alpine ski racing, recreational skiing resulted in a lower GRF of ~ 2000 N (Müller & Schwameder, 2003). The *paral-*

lel ski steering skiing mode is determined by a high-loaded outer leg and a low-loaded inner leg. In contrast, an increased co-loading of the inner leg is one of the main criteria of the *carving in long radii* skiing mode (Wörndle et al., 2007). Similar to the kinematic results, the kinetic results from the present study partly support, but are also partly in contrast to our hypotheses and the general principles of the Austrian Ski Teaching Concept. First, in agreement with our hypothesis, the lowest peak GRF was found for the *parallel ski steering* skiing mode, with no differences between *carving in long radii* and *individual technique* skiing modes. The determined mean total GRF of $1.2 - 1.3 \times$ body weight, corresponding to absolute GRFs of 850–920 N, and the total peak GRF of $1.5 - 1.6 \times$ body weight (1050–1130 N) in the present study were low compared with the above-mentioned literature. The GRF in this present study were determined by pressure insoles, because insoles are lighter than three-dimensional dynamometers (0.2 vs 3.6 kg) and do not increase standing height. They have the advantage not to significantly influence skiers' technique (Stricker et al., 2010). However, pressure insoles underestimate GRFs by about 20% compared with three-dimensional dynamometers (Stricker et al., 2010), and therefore, these data should be analyzed and interpreted carefully. Nevertheless, the present results demonstrate that GRFs of older skiers in recreational skiing may not reach extreme values, as reported in earlier studies. Another hypothesis of the present study was to find higher GRFs and an increased co-loading of the inner leg for the *carving in long radii* skiing mode compared with the *parallel ski steering* skiing mode. Peak GRF, but not mean GRF, was significantly lower for *parallel ski steering* compared with *carving in long radii* and *individual technique* skiing modes. Theoretically, the GRF is directly proportional to the skiing speed (v^2) and indirectly proportional to the turn radii. Potential additional variables influencing GRFs include: ski edge angle, ski terrain and snow conditions. Ski terrain and snow conditions in the present study were consistent for all subjects and throughout all the skiing modes. The *individual technique* resulted in a greater speed of (~ 43 km/h) than *carving in long radii* (~ 38 km/h) and *parallel ski steering* (~ 28 km/h). The *parallel ski steering* mode was characterized by longer "traversing parts" and hence a greater horizontal skiing distance per turn (Fig. 1), followed by a turning phase (steering phase) with lower turn radii (~ 7 m), compared with the *carving in long radii* (~ 9 m) and *individual technique* skiing modes (~ 12 m). This is due to a relatively long initial phase and second steering phase of the *parallel ski steering* mode (Müller & Schwameder, 2003; Wörndle et al., 2007). Based on Newton's law, the GRFs should be substantially lower during *parallel ski steering*, compared with *carving in long radii* and greater during *individual technique*. The peak GRF of the *parallel ski steering* mode was significantly lower, compared with the *carving in long radii* and *individual technique* modes (Table 2). The results of the peak GRFs are in agreement with the theoretical calculations and may be mainly determined by the turn radii during the steering phase. However, the data of the mean GRFs in the present study did not support these considerations. As mentioned above, factors like ski edge and attack angle may play an important role in the GRFs. Both are greater in skidded, compared with carved skiing modes (Müller & Schwameder, 2003; Müller & Schiefermüller, 2009).

Similar to the kinematic results, no differences in the GRFs were observed between *carving in long radii* and *individual technique* skiing modes. From this standpoint, the *individual technique* skiing mode is more similar to the *carving in long radii* mode than to the *parallel ski steering* skiing mode. However, the co-loading of the inner leg demonstrated mixed results: the greatest co-loading of the inner leg was determined for the *individual technique* skiing mode (38.8%) and the lowest for the *carving in long radii* skiing mode (32.5%), while the *parallel ski steering* skiing mode resulted in a co-loading of 35.6%. The study results revealed that a force distribution between the outside and the inside leg of 60:40% to 70:30% may indicate a preferred skiing style for older recreational skiers.

Recreational alpine skiing is characterized by repetitive turns with dynamic and static muscle work (Müller & Schwameder, 2003; Kröll et al., 2009). Additionally, different skiing modes and individual skiing styles result in lower or higher skiing positions (Wörndle et al., 2007). Because alpine skiing is a complex activity, RKA and MKA are discussed together. In the present study, significant positive correlations between RKA and LA for *carving in long radii* and *individual technique* skiing modes were observed. However, the HR_{ave} response was not related to the RKA. No significant correlations were found between MKA and LA, while the MKA demonstrated significant negative correlations to HR_{ave} in *parallel ski steering* and *carving in long radii* skiing modes. Pronounced flexing and extending of the legs and hence a greater RKA is helpful in initiating a turn in alpine skiing. However, increased dynamic exercise potentially involves greater active muscle mass and consequently LA increases (Gollnick et al., 1986; Kayser et al., 1994; Magnusson et al., 1994; Hofman et al., 1996). Skiing in a lower position increased the HR_{ave} response, which is in agreement with Rundell (1996), Rundell et al. (1997), Foster et al. (1999), Leirdal et al. (2006) and Szmedra et al. (2001). This may be due to the fact that perfusion is reduced in a low position, as reported by Szmedra et al.

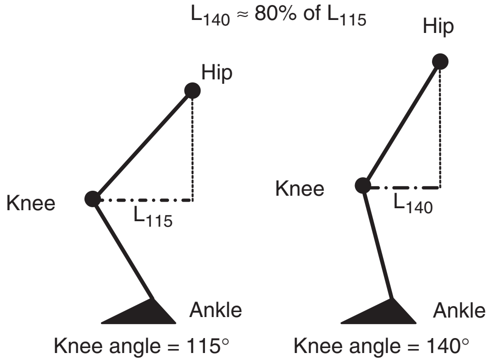

Fig. 5. Estimated changes of the lever arm for skiing positions at 140° (L_{140}) vs 115° (L_{115}). The lever arm is directly proportional to the torque acting on the knee axis.

(2001). This in turn increases HR to maintain blood flow. Additionally, muscle recruitment of knee extensors and hence metabolic involvement is influenced by the knee angle (Pincivero et al., 2004; De Ruiter et al., 2008). A lower knee angle may result in a greater lever arm of the external load, which is directly proportional to the torque acting on the muscle. The ankle, knee and hip angles are typically reduced when a skier is lowering the skiing position but the center of mass along the sagittal plane remains in a relatively stable position without a wide range of motion (Schiefermüller et al., 2005; Tjorhom et al., 2007). Individual knee angles of the higher-loaded outer leg in the present study ranged between ~ 115° and ~ 140° (Table 2). Figure 5 demonstrates a rough estimation of the changes in the lever arm for a low (115°) vs high (140°) skiing position. The estimated lever arm in a more extended skiing position (140°) was reduced by ~ 20%, compared with a lower skiing position (115°). Consequently, a greater knee angle may result in a substantial reduction in knee extensor muscle recruitments, hence metabolic involvement. However, this is just an estimation and the effect of changes in the lever arm on muscle load can only be answered in detail via three-dimensional kinematics, kinetics and inverse dynamics.

Generally, muscle activity is related to external forces acting on an athlete (Kyröläinen et al., 2005) and may affect the physiologic response. The mean GRF of all three skiing modes did not differ, in the present study, while the peak GRF of the *parallel ski steering* skiing mode was significantly lower, compared with *carving in long radii* and *individual technique* skiing modes. Nevertheless, the inter-personal variations in both the mean and peak GRFs were substantial (Table 2). Interestingly, none of the determined kinetic variables in the present study were related to LA and HR_{ave}. Possible explanations would be that skiers self-regulate external loads by changing their body position or by an alteration in muscle recruitment.

Perspectives

The present study demonstrated that older skiers responded with a large inter-personal variation in the physiological, kinematic and kinetic variables within all skiing modes. Descriptive results indicated that skiers skied in a more upright and static skiing style with a lower peak GRF during *parallel ski steering* compared with *carving in long radii* and *individual technique*. Even though the run times were significantly different between skiing modes, the mean GRF did not differ. The absence of correlations between kinetic and physiological variables indicates that changes in the mean GRF may be compensated by the skiing position and skiing style to keep the total workload constant. Based on our findings for the relationships between biomechanics and physiology, it seems that dynamic skiing styles lead to a greater amount of muscle work. Muscle fiber recruitment may be increased, leading to an increase in LA (Gollnick et al., 1986). Similar to speed skating (Rundell, 1996), lower skiing positions in the present study increased HR_{ave}. This may be due to a decreased blood flow and a reduced lever arm for the external torques in a low skiing position. Therefore, from a physiological standpoint skiing with a greater MKA [Fig. 4(c) and (d)] combined with a lower RKA [Fig. 4(a) and (b)] can be recommended for older recreational skiers.

Key words: dynamic, metabolism, muscle work, kinematics, kinetics, perfusion, skiing position, static.

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