

# Static Flexibility as a Correlate of Skate Roller Skiing Economy Within Collegiate Cross-Country Skiers

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**Abstract** This study examined the correlational relationships between measures of flexibility and economy (E) during submaximal skate roller skiing in collegiate cross-country skiers. Twelve male competitive skiers (Mean±SD: 21±3 years) completed seven flexibility tests including total body rotation, lateral flexion of spine, shoulder rotation, standing and lying horizontal hip abduction, modified sit-and-reach test, and passive leg raise. During a second lab visit, subjects performed three 10-min roller skiing trials at 65%, 75%, and 85% of maximal heart rate (HR) on an oval indoor track while submaximal oxygen consumption ( $\text{VO}_2$ ) and HR were measured via a portable metabolic system. Two methods were used to define roller skiing E: 1) The slopes of the regression lines between  $\text{VO}_2$  and HR with roller skiing speed for each subject (i.e.,  $\text{VO}_2$  and HR slopes); 2) The predicted  $\text{VO}_2$  and HR from the individual regression lines when solved for common “slow” (248 m/min) and “fast” (309 m/min) roller skiing speeds. Using Pearson product-moment correlations, there were no significant correlational relationships between any measure of flexibility with any measure of E ( $r = -0.42$  to  $0.68$ ). These results suggest that flexibility is not a determinant of submaximal skate roller skiing E in collegiate male cross-country skiers.

**Keywords** Range of motion, Endurance athletes, Skating, Steady-state, Gender

## 1. Introduction

Economy (E) is most often defined as the rate of oxygen consumed per unit mass (ml/kg/min) to perform a specific task [6], such as running at a specific speed and grade on a treadmill. While determinants of E among endurance athletes have been well studied, no area is more controversial than the influence of static joint flexibility (hereafter referred to as flexibility) on running E [5, 9, 12, 15, 20]. Several studies, for example, have suggested that less flexible runners have better running E than more flexible runners [9, 12, 15], while other studies found neither negative nor positive correlations between flexibility and E [5,20]. A commonly cited mechanism underlying the potential link between flexibility and running E is that passive support by less flexible structures in the body will allow the runner to expend less energy during the deceleration-acceleration phase of ground impact [5].

With the exception of a single study evaluating the influence of dance training on changes in junior cross-country skier flexibility [1], research has not yet addressed the possible relationship between flexibility and cross-country skiing E. There are several distinct differences between cross-country skiing and distance running, however,

that could influence any possible relationship between flexibility and cross-country skiing E. First, the propulsive phase of cross-country skiing involves both upper and lower body musculature via skis and poles whereas running is more purely a lower body activity. Second, cross-country skiing techniques involve a distinct gliding phase, whereas distance running has a distinct deceleration-acceleration phase caused by the relatively large ground impact force with each footfall and no glide phase. Thirdly, joint motion for running is primarily in the sagittal plane, but the skate style of cross-country skiing (the focus of the present study) involves joint motion in all three planes. Cross-country skiing performance is also considered more skill dependent than distance running due to the complex interaction of changes in technique with snow conditions, terrain, as well as choice of ski equipment and wax [23]. Finally, cross-country skiing is a sport that continues to evolve due to advances in training, equipment, and ski techniques. For example, Nilsson et al. [22] documented the skate skiing style as having four kinematically distinct techniques [22], which has more recently been updated to seven distinct techniques by Andersson et al. [3]. Finally, an important component to some of these newer skiing techniques is the ability to take advantage of the upper body's power generating ability [2].

Given the degree to which skiing technique has evolved to meet the demands of modern ski racing, it seems reasonable to speculate that flexibility may influence cross skiing E, and thus possibly influence skiing performance, in a yet undefined manner. Thus, the present study sought to explore

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the correlational relationships between a number of static flexibility measures (i.e., those that include both upper and lower body joints; single and multi-joint tests) and measures of skate roller skiing economy. This study also used roller skiing as a surrogate for on-snow skiing to help control for the confounding influences of changing snow conditions on the energy cost of skiing. Given the exploratory nature of this study, as well as to improve generalizability of the findings to the current research literature, this study used similar methodological and analytical strategies (i.e., correlational analyses) as those researching flexibility and running E.

## 2. Methods

### 2.1. Subjects and Testing Procedures

To avoid the possible confounding influence of gender and age on this study, only male cross-country skiers who were 18-26 years of age, and had at least three years of recent Nordic ski racing experience, were recruited from a Division I college ski team and a local elite Nordic team. Given their age and caliber, all of these skiers could be considered endurance generalist skiers who race both classic and skate techniques at distances ranging from five to 30 km. All subjects read and signed an informed consent document explaining the testing procedures and potential risks of the study prior to participation. The testing procedures were approved by the Montana State University Institutional Review Board.

Each subject participated in two testing sessions (hereafter referred to as Session 1 and 2) within a two-week period. Session 1 occurred within the Movement Science / Human Performance Laboratory whereas Session 2 was conducted in the Worthington Arena on the Rob Stark indoor oval track at Montana State University. The purpose of Session 1 was to collect anthropometric and demographic data (e.g., age, body mass and height), administer a treadmill-based maximal oxygen uptake ( $\text{VO}_{2\text{MAX}}$ ) test, as well as administer a battery of flexibility tests. For the present study, flexibility was defined as the complete range of motion (ROM) possible for a single- or multi-joint action [11], as measured with single-joint (e.g., knee flexion and extension) or multiple-joint ROM tests (e.g., sit-and-reach test). The purpose of Session 2 was to measure E during three submaximal speeds of indoor roller skiing. Roller skiing, a skiing-specific form of cross training on paved roads for cross-country skiers, was used as an alternative to snow skiing to avoid the confounding influences of changing snow conditions on measures of E. Subjects were instructed to maintain the same level of physical activity throughout their study participation except 48 hours prior to each test session where subjects were instructed to refrain from high intensity exercise.

**Session 1 –  $\text{VO}_{2\text{MAX}}$  and Flexibility Testing.** Subjects completed an incremental treadmill test to exhaustion to determine  $\text{VO}_{2\text{MAX}}$  and maximal heart rate ( $\text{HR}_{\text{MAX}}$ ). Individual  $\text{HR}_{\text{MAX}}$  values were used for controlling roller

skiing intensity during Session 2, while the  $\text{VO}_{2\text{MAX}}$  values were used purely for descriptive purposes. After measuring body mass and height, subjects completed a warm-up on a treadmill at a self-selected speed and grade for 10 minutes. The ski walking/running protocol started with a speed of 99.2 m/min and a grade of 6 % with speed and grade increasing by 8 m/min and 2%, respectively, for each successive stage. This treadmill-based protocol was used because a roller skiing-based maximal protocol was not possible given wintery outdoor weather conditions and that the indoor track used for Session 2 was not so freely available.

The first 3-5 stages of the  $\text{VO}_{2\text{MAX}}$  test protocol lasted four minutes each and were discontinuous (three mins active plus one min standing rest) for the purpose of measuring fingertip blood lactate (data not reported), while each stage thereafter lasted one minute until volitional exhaustion. During the  $\text{VO}_{2\text{MAX}}$  test, subjects used Nordic ski poles with rubber tips to simulate diagonal stride skiing by poling with the upper body while walking/running. As the speed of the treadmill increased across stages, subjects changed from long walking strides to hill-bounding (running with poles). Subjects were considered to have reached  $\text{VO}_{2\text{MAX}}$  if two of the three following criteria were satisfied: 1) Respiratory exchange ratio (RER)  $\geq 1.1$ ; 2) Subject's relative oxygen uptake did not increase more than 2.5 ml/kg/min despite progressing to another stage at the end of test (i.e., increased external workload); 3) Measured  $\text{HR}_{\text{MAX}}$  was within  $\pm 10$  BPM of age predicted maximal heart rate (APMHR). Each  $\text{VO}_{2\text{MAX}}$  test was completed within 15-20 minutes.

Within 2-5 minutes of completing the  $\text{VO}_{2\text{MAX}}$  test warm-down, administration began for seven tests of shoulder, trunk and lower limb flexibility were performed over a period of 30 minutes. Five of these tests were performed on both the left and right sides of the body. Two complete trials of all flexibility measures were consecutively recorded on each subject while not wearing shoes. The order of flexibility tests were counterbalanced across subjects and all measurements were taken by the same investigator. The better of two trials for each test was used for subsequent analyses, where the "best" score indicated a greater ROM. All measures were recorded to the nearest 0.1 cm or one degree.

**Total Body Rotation (TBR).** The TBR test is a measure of multi-joint ROM that requires whole-body rotation in the transverse plane starting from a standing position. Test performance can involve motion at the ankles, knees, trunk, shoulders and shoulder girdle, as well as along the spine. The test was administered on both left and right sides of the body using the procedures described by Hoeger and Hoeger [14].

**Lateral Flexion of Lumbar Spine (LFLS).** With this test, lateral flexion of the spine was measured on both sides. Subjects began by standing with their back against a wall, both arms at their sides, and the wrists in a neutral position. Next, the third finger from one hand was moved down along the lateral aspect of the same side leg using lateral flexion in the frontal plane (e.g., left-lateral flexion of the lumbar spine

for the left side) until further flexion was no longer possible. Both beginning and end points of the third finger were marked on the body with a pen. Using a ruler, the absolute distance between these two marks were recorded. This test was performed on both the left and right sides of the body.

**Shoulder Rotation (SR).** The SR test measured the degree of simultaneous left and right shoulder rotation in the frontal plane. The test is assumed to be a composite measure of both shoulder joint and shoulder girdle flexibility. The test was administered using the procedures described by Hoeger and Hoeger [14].

**Standing and Lying Horizontal Hip Abduction (SHHA & LHHA).** For the standing test (SHHA), subjects stood against a wall with their knee held in a 90° position. From this position, the subject actively abducted the hip horizontally as far toward the wall as possible. During the test, subjects were allowed to grasp the wall for stability. Using a handheld goniometer, horizontal hip abduction angle in the transverse plane was measured for both left and right sides, as well as with subjects in a supine position (LHHA). The SHHA test is the same as the “external hip rotation” described by others [5, 9].

**Modified Sit-and-Reach (MSR).** The MSR is a multi-joint ROM test that requires motion in the sagittal plane from a seated position. The test was administered using the procedures described by Hoeger and Hoeger [14].

**Passive Leg Raise (PLR).** The PLR test evaluated the flexibility of the hamstring muscles across the hip joint. While laying supine on a padded mat, one leg of the subject was held against the mat while the other leg was passively flexed (by the investigator) at the hip while keeping the knee fully extended. The leg was raised to the point of mild discomfort as reported by each subject. With a goniometer, hip flexion angle between the chest and the raised leg was measured for both left and right legs. Both Craib *et al.* [9] and Gleim *et al.* [12] used this test as part of their battery of flexibility measures.

**Rational for Flexibility Tests.** The exact choice of flexibility tests were based upon a combination of factors specific to this study. Some tests were included because of their use in previous studies (e.g., sit-and-reach, SHHA, LHHA), while other tests were included because test performance focused upon specific joint structures (e.g., SR performance dependent upon shoulder joint and girdle flexibility). It was also desirable to use flexibility tests with measurement protocols and normative tables documented in the literature. Finally, given that skate roller skiing involves major joint motion in all three planes of motion, it seemed reasonable to include tests that emphasized flexibility across all three planes: Frontal (LFLS, SR), sagittal (MSR, PLR), and transverse (TBR, SHHA, LHHA).

**Session 2 - Submaximal Rollerski Testing.** This session assessed indoor roller skiing economy at three submaximal steady-state speeds. After completion of a 15-min roller skiing warm-up at a self-selected speed (which also served to habituate subjects to roller skiing on the indoor track), subjects performed three 10-min trials at preset target heart

rates (65%, 75%, and 85% of  $HR_{MAX}$ ). Stretching of any kind was not allowed prior to testing, during the warm-up, or between roller skiing trials. The indoor track was oval in shape (216.1 m/lap in the center lane) and maintained at approximately 20-23°C and 30-45% relative humidity. High visibility cones were placed on the track to mark the roller skiing path for all subjects. In doing so, the impact of roller skiing the corners of the track was minimized. In fact, none of the subjects complained afterward of any roller skiing difficulties. During all trials, subjects used a wrist-worn HR monitoring watch set with upper and lower limit audible alarms around  $\pm 3$  BPM of their target HR zones. The audible alarm would go off when roller skiing HR was too high or low which informed the subject that their roller skiing intensity was too high or too low, respectively. Ideally, subjects found a roller skiing speed within the first 2-3 mins of each trial that kept their HR within the desired zone. During each trial, subjects wore a portable metabolic system mounted to a small backpack to collect minute-by-minute HR and  $VO_2$  data. In the event that the direction of travel around the track (clockwise versus counterclockwise) was an unknown confounder, subjects rollerskied two trials in one direction and one trial in the opposite direction. Lastly, subjects were instructed to use the G3 skating technique on the straight portions of the track and the G4 technique on the corners (commonly referred to as V2 and V2 alternate, respectively) [3]. The direction of travel for each trial, as well as the order of target heart rates tested, were counterbalanced across subjects. All subjects used the same model of rollerski for testing (provided by investigators), but subjects did use their own ski poles and boots. Lastly, lap times during the last five minutes of each trial were recorded and averaged for subsequent calculation of average rollerski speed for each trial.

## 2.2. Instrumentation

**Indirect Calorimetry.** Oxygen uptake during  $VO_{2MAX}$  testing was measured with a TrueMax 2400 Metabolic Measurement System (Parvo Medics, Sandy, UT, USA). Subjects wore a nose-clip and inspired room air through a mouthpiece with one-way valves. Prior to each test, the oxygen and carbon dioxide gas analyzers were calibrated with gases of known composition while the ventilation measurements were evaluated using a calibrated 3-liter syringe (Hans Rudolph, Kansas City, MO, USA). Measures of  $VO_2$  were recorded in 20-sec intervals and a telemetry-based heart rate monitor (Accurex Plus; Polar Electro, Inc., Lake Success, NY, USA) was used to record average heart rate every five seconds (i.e., for assessment of  $HR_{MAX}$ ).

**Submaximal Rollerski Test.** Average heart rate was recorded every 60 s via telemetry to a wrist-worn HR watch (Accurex Plus; Polar Electro, Inc., Lake Success, NY, USA), while a portable metabolic system (Oxycon Mobile; Viasys Healthcare, Cardinal Health Inc., Dublin, OH, USA), mounted to a tight-fitting modified hydration backpack (Slipstream; Camelbak Products, LLC; Petaluma, CA)

recorded  $\text{VO}_2$  values each minute. The same model of rollerskis (Skating 610; Marwe, Hyvinkään KumiOy, Finland) were mounted with either pilot (Salomon Sports, Annecy, France) or Rotefella NNN (Garmont USA Inc., Williston, VT, USA) bindings for all roller skiing trials. A calibrated measuring wheel (Rolatape® Professional Series, Spokane, WA, USA) was used to measure the length of the track.

**Flexibility Tests and Anthropometrics.** The MSR, TBR, and SR tests were determined using the Acuflex® I, II and III (Novel Products, Inc., Rockton, IL, USA), respectively, which are commercial products specifically designed for these flexibility tests. The other flexibility tests used a stainless Baseline® goniometer (Country Technology Inc., Gays Mills, WI USA) or a gravity-type goniometer (Leighton Flexometer Inc., Spokane, WA, USA). Body height and mass were measured to the nearest 0.1 cm and 0.1 kg, respectively using a Health-o-Meter beam scale (Continental Scale Corp., Bridgeview, IL).

### 2.3. Data Processing

For the purpose of this study, submaximal  $\text{VO}_2$  and HR were both used as markers of roller skiing E. In general, most previous running E research has relied upon correlated measures of E at fixed treadmill running speeds with measures of flexibility [9, 12, 15]. In the present study, roller skiing at fixed speeds was not possible without an oversized treadmill, so two separate methods for computing roller skiing E were applied to the three roller skiing trials for subsequent correlational analyses with the measures of flexibility. First, the last four minutes of  $\text{VO}_2$  and HR data from the roller skiing trials were averaged for each subject. Next, these average  $\text{VO}_2$  and HR values (dependent variables) were plotted against average roller skiing speed (independent variable) to derive a linear equation using standard least-squares regression techniques. The slope coefficients from these regression lines, hereafter referred to as  $\text{VO}_2$  and HR slopes (units of ml/kg/m and beat/m, respectively), were used as indicators of roller skiing E. Previous running studies [5, 28] using the same type of E variable suggested two advantages of expressing E in this manner: 1) The relative energy cost is independent of travel speed, and 2) the conceptual understanding of E improves because values for E increase as economy improves. In contrast, when expressing E in the traditional units of ml/kg/min the values of E decrease as economy improves.

The second method for computing roller skiing E relied on using the same individual regression equations for  $\text{VO}_2$  and HR as described above. Specifically, these equations were used to compute point estimates of  $\text{VO}_2$  and HR for two roller skiing speeds that were common to all of the subjects tested. The variables derived from this analysis, corresponding to the slowest and fastest common roller skiing speeds, were referred to as the slow and fast common speed  $\text{VO}_2$  and HR for each subject (i.e., four new variables per subject). The derivation of the common speed  $\text{VO}_2$  and

HR values are conceptually similar to the running E variables reported by others (i.e., the energy cost to perform a specific task) [9, 11, 12, 15]. Thus, there were a total of six roller skiing E variables:  $\text{VO}_2$  and HR slopes,  $\text{VO}_2$  and HR at the “slow” common speed, as well as  $\text{VO}_2$  and HR at the “fast” common speed.

Lastly, it should be noted that the use of HR as an indicator of E was considered exploratory for this study and unique for studies of flexibility and E. It was hypothesized that HR could be more responsive to changes in roller skiing speed and intensity than measures of  $\text{VO}_2$  due to potential changes in body posture with increasing roller skiing speed.

### 2.4. Statistical Analyses

Intraclass reliability for internal consistency ( $R_{XX}$ ) across minutes 7-10 for the relative  $\text{VO}_2$  and HR data, as well as for three successive measures of lap time, were evaluated for the three roller skiing intensities prior to averaging to ensure adequate reliability. Specifically, these data were evaluated with a 1-factor repeated measures ANOVA and calculations of the standard error of measurement (SEM) (Baumgartner & Jackson, 1995). The ANOVA analyses were also used to detect significant differences between the mean values across minutes (i.e.,  $\text{VO}_2$  and HR) and measures of lap time, all of which were performed at an alpha level of 0.05.

Measures of roller skiing E ( $\text{VO}_2$  and HR slopes, as well as  $\text{VO}_2$  and HR for slow and fast common-speeds) were correlated with individual measures of flexibility using the Pearson product-moment correlations and Fischer's Z transformation to calculate 99% confidence intervals. Given the number of correlations being performed, these evaluations were performed at the 0.01 alpha level for testing significance from a zero correlation. All statistical analyses were performed using the Statistical Package for the Social Sciences software (SPSS V12.0, SPSS Inc., Chicago, IL, USA). According the procedures outlined by Cohen [7], and assuming a high reliability (e.g.,  $R_{XX} \geq 0.90$ ), a sample size of at least 11-12 subjects were required to detect a correlation of 0.75 or more at a power of 0.80 and alpha of 0.01.

## 3. Results

Twelve male cross-country skiers (Mean $\pm$ SD: 21 $\pm$ 2.5yrs, 1.83 $\pm$ 0.07 m body height, 76.7 $\pm$ 6.8 kg body mass) completed both testing sessions and self-reported an average 11 years of ski racing experience and 507 $\pm$ 95 hours of training during the previous year. Measures for  $\text{VO}_{2\text{MAX}}$  averaged 4.6 $\pm$ 0.5 l/min, or 60.4 $\pm$ 3.4 ml/kg/min relative to body mass, while HR $_{\text{MAX}}$  averaged 193 $\pm$ 6 BPM.

Measures of  $R_{XX}$  for HR (0.97-0.98),  $\text{VO}_2$  (0.98-0.99), and lap time (0.93-0.99) were high for all three RS intensities. In addition, the ANOVA analyses did not indicate significant differences among mean values being compared ( $P > 0.05$ ). Lastly, calculations of SEM were low for HR ( $\pm$ 0.6-0.8 BPM), relative  $\text{VO}_2$  ( $\pm$ 0.33-0.38 ml/kg/min) and lap time ( $\pm$ 0.6-1.4 secs). Collectively, these results indicate a high

degree of consistency for minute-to-minute measures of  $\text{VO}_2$  and HR (i.e., steady-state was achieved), as well as for successive measures of lap time.

### 3.1. Flexibility and Rollerski Testing

Table 1 summarizes the flexibility test measures, with values for left and right sides reported separately. The results for the rollerski tests are summarized in Table 2. Submaximal  $\text{VO}_2$  was expressed relative to the total mass of transport during roller skiing, which included both body mass and equipment mass (Mean $\pm$ SD; 4.9 $\pm$ 0.1 kg). The equipment consisted of ski poles (0.34 $\pm$ 0.01 kg), ski boots (1.34 $\pm$ 0.10 kg), roller skis (2.1 kg), as well as the HR monitoring and portable metabolic systems (1.16 kg).

Figures 1 and 2 were created to illustrate the derivation of individual  $\text{VO}_2$  and HR slope variables, as well as demonstrate the degree of individual variability with  $\text{VO}_2$  and HR responses. Figure 1, for example, shows three subjects with very different  $\text{VO}_2$  slopes due to similar  $\text{VO}_2$  values ( $\pm 2$ -3 ml/kg/min) at slower speeds but very different  $\text{VO}_2$  values at high speeds. In addition, Subjects 1 and 5 had almost identical  $\text{VO}_2$  values for all three roller skiing target intensities, but their roller skiing speeds were very different (Subject 5 was much faster at both 75% and 85% intensities). Similarly, Figure 2 shows three subjects with very different relationships between HR and roller skiing speed which resulted in different HR slopes. The  $r$  and SEE values for

individual  $\text{VO}_2$  regression equations ranged 0.88-0.99 and  $\pm 0.50$ -4.14 ml/kg/m, respectively, while the individual HR regression equations ranged 0.94-0.99 and  $\pm 0.5$ -7.2 BPM, respectively.

### 3.2. Correlational Analyses

**$\text{VO}_2$  or HR Slopes.** The correlational analyses revealed no significant relationships between any measure of static flexibility with either  $\text{VO}_2$  or HR slopes (Table 1). As examples, Figures 3A and 3B show the relationship between  $\text{VO}_2$  and HR slopes, respectively, and shoulder rotation (SR) flexibility. Both figures illustrate weak positive, though non-significant, correlational relationships between these variables ( $r = +0.49$  and  $+0.31$ , respectively).

**Common Speed  $\text{VO}_2$  and HR.** The “slow” and “fast” common speeds used to predict  $\text{VO}_2$  and HR from individual regression equations were 248 and 309 m/min, respectively. The vertical lines within Figures 1 and 2 demonstrate how these common speeds fell within the actual roller skiing speeds for the subjects highlighted. Predicted  $\text{VO}_2$  and HR at 248 m/min averaged (Mean $\pm$ SD) 32.99 $\pm$ 8.11 ml/kg/min and 140 $\pm$ 8 BPM, respectively, while the same variables averaged 39.52 $\pm$ 9.97 ml/kg/min and 162 $\pm$ 9 BPM, respectively, for the 309 m/min speed. When correlating these two predicted variables against each of the static flexibility measures, not a single relationship was significant at an alpha of 0.01 (Table 3).

**Table 1.** Summary statistics (Mean $\pm$ SD, Range) for seven tests of flexibility ( $n = 12$ ) including correlation coefficients between individual flexibility test variables and roller skiing oxygen consumption ( $\text{VO}_2$ ) slope (ml/kg/m) and heart rate (HR) slope (beats/m) variables

Name of Flexibility Test (units)		Mean $\pm$ SD	Range	$\text{VO}_2$ Slope Correlation (95% CI)	HR Slope Correlation (95% CI)
R-TBR	Right Total Body Rotation (cm)	28.2 $\pm$ 13.5	3.8 – 50.3	-0.03 (-0.71-0.68)	-0.13 (-0.76-0.62)
L-TBR	Left Total Body Rotation (cm)	32.2 $\pm$ 13.0	11.2 – 52.8	0.05 (-0.67-0.72)	-0.10 (-0.74-0.64)
R-LFLS	Right Lateral Flexion of Lumbar Spine (cm)	24.6 $\pm$ 3.6	19.3 – 29.8	-0.14 (-0.76-0.62)	-0.08 (-0.73-0.65)
L-LFLS	Left Lateral Flexion of Lumbar Spine (cm)	25.1 $\pm$ 3.4	19.5 – 30.0	-0.38 (-0.85-0.43)	0.09 (-0.65-0.74)
SR	Shoulder Rotation (cm)	80.3 $\pm$ 13.0	54.6 – 96.5	0.49 (-0.31-0.88)	0.31 (-0.49-0.83)
R-SHHA	Right Standing Horizontal Hip Abduction (degrees)	67.2 $\pm$ 9.5	53.5 – 86.5	-0.27 (-0.81-0.52)	0.06 (-0.66-0.73)
L-SHHA	Left Standing Horizontal Hip Abduction (degrees)	66.4 $\pm$ 13.8	43.5 – 85.0	-0.14 (-0.76-0.62)	0.04 (-0.67-0.72)
R-LHHA	Right Lying Horizontal Hip Abduction (degrees)	70.6 $\pm$ 7.1	57.5 – 80.0	0.03 (-0.68-0.71)	-0.05 (-0.72-0.67)
L-LHHA	Left Lying Horizontal Hip Abduction (degrees)	66.3 $\pm$ 8.5	49.5 – 79.0	-0.34 (-0.84-0.47)	-0.42 (-0.86-0.39)
MSR	Modified Sit-and-Reach (cm)	39.9 $\pm$ 7.4	27.7 – 51.6	0.12 (-0.63-0.75)	-0.32 (-0.83-0.39)
R-PLR	Right Passive Leg Raise (degrees)	98.8 $\pm$ 14.6	72.5 – 122.5	0.14 (-0.62-0.76)	-0.27 (-0.81-0.52)
L-PLR	Left Passive Leg Raise (degrees)	98.1 $\pm$ 13.5	75.0 – 120.0	0.15 (-0.61-0.77)	-0.12 (-0.75-0.63)

\* None of the correlations differed significantly from zero ( $P > 0.05$ ).

**Table 2.** Summary statistics from the submaximal roller ski tests (Mean $\pm$ SD) ( $n=12$ )

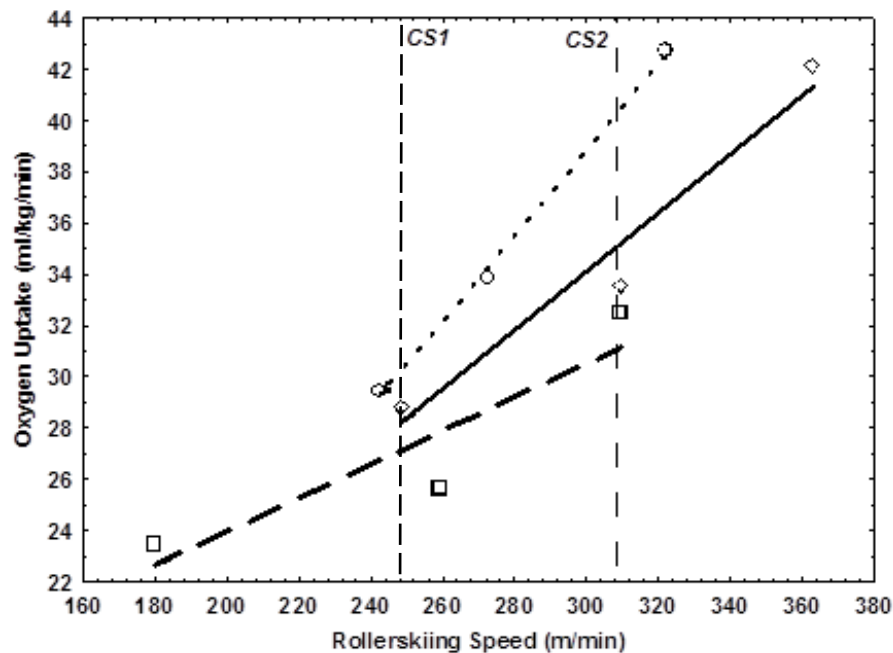
Target % of $\text{HR}_{\text{max}}$	Time per lap(s)	Speed (m/min)	$\text{VO}_2$	HR (BPM)	Actual % of $\text{HR}_{\text{MAX}}$
65	65.8 $\pm$ 12.0	202.7 $\pm$ 33.3	25.7 $\pm$ 4.3	127 $\pm$ 4	65.7
75	49.5 $\pm$ 5.1	264.5 $\pm$ 25.6	28.8 $\pm$ 4.6	145 $\pm$ 5	75.0
85	41.3 $\pm$ 2.7	315.3 $\pm$ 20.9	37.0 $\pm$ 4.4	165 $\pm$ 5	85.4

NOTE:  $\text{HR}_{\text{MAX}}$  = maximal heart rate; HR = submaximal heart rate;  $\text{VO}_2$  = submaximal oxygen uptake relative to total mass (body + equipment) in units of ml/kg/min

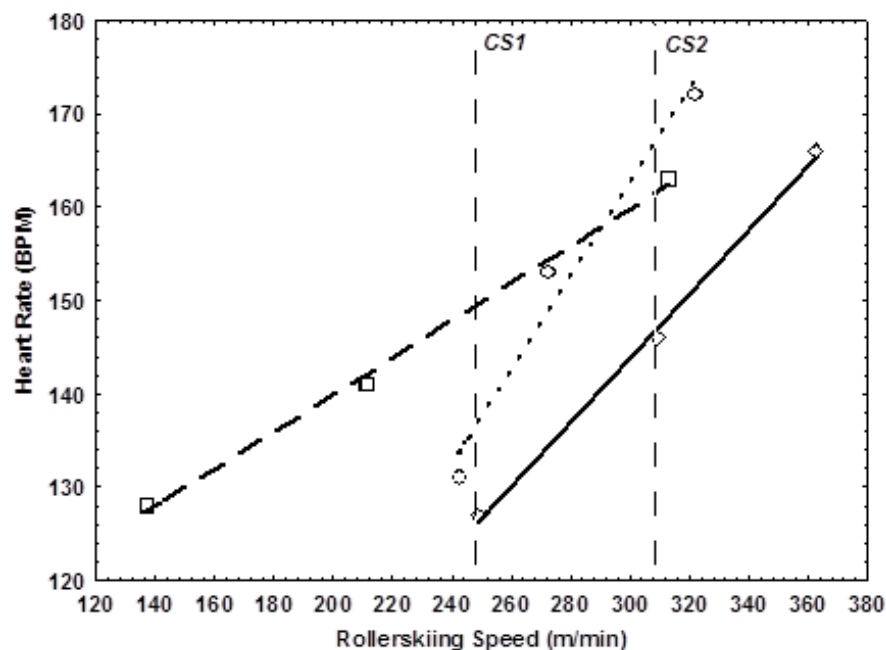
#### 4. Discussion

The primary finding of this study was that all measures of skate roller skiing E correlated non-significantly with multiple measures of static flexibility in competitive male cross-country skiers. These findings may suggest that neither high nor low degrees of flexibility, or ROM, as assessed by

this study is required for optimizing skate roller skiing E. Since there are no prior published studies evaluating the influence of flexibility on roller skiing E or any other determinant of cross-country skiing performance, the present study can only be compared with the running E literature.



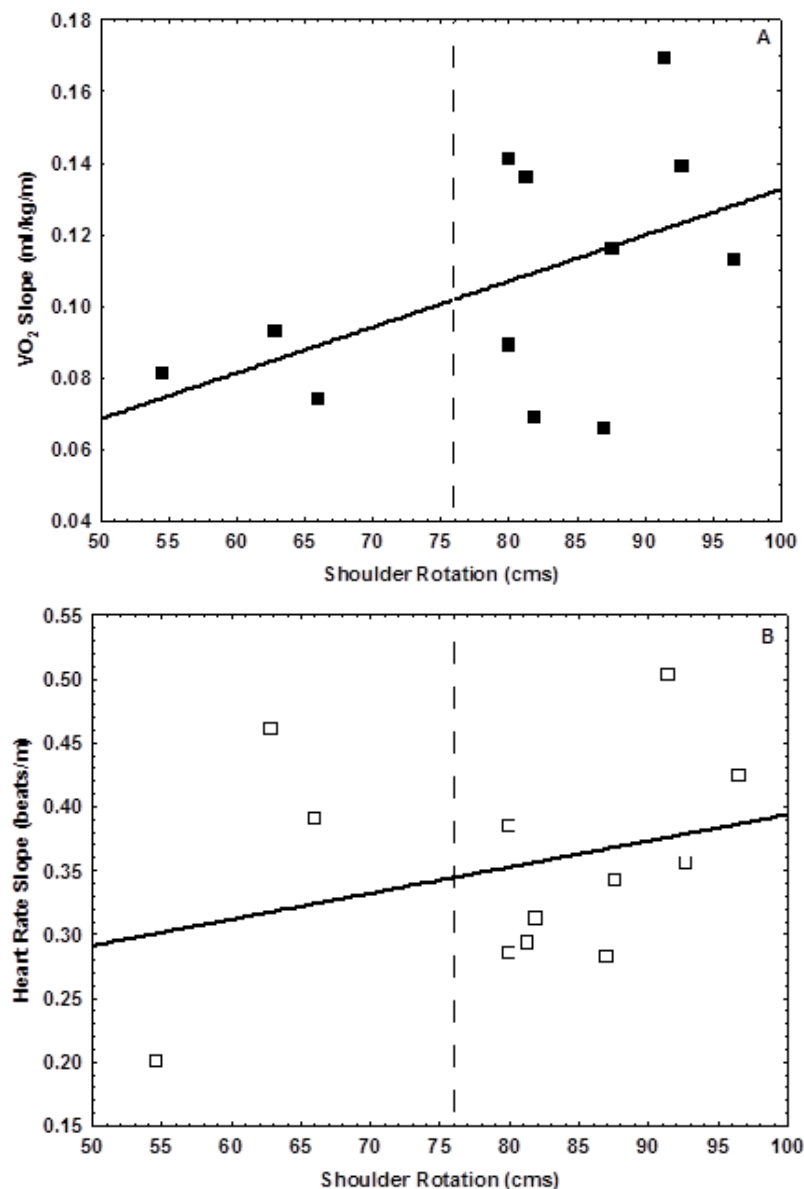
**Figure 1.** Three example relationships between steady-state oxygen uptake ( $\text{VO}_2$ ) and roller skiing speed for three subjects: Subject 1:  $\text{VO}_2 = 0.17 \times S - 11.68$  ( $r > 0.99$ ), open circles with short-dashed line; Subject 4:  $\text{VO}_2 = 0.07 \times S + 10.78$  ( $r = 0.91$ ), open diamonds with long-dashed line; Subject 5:  $\text{VO}_2 = 0.12 \times S - 0.62$  ( $r = 0.98$ ), open squares with solid line. Vertical dotted lines correspond to the “slow” and “fast” common speeds (CS1 and CS2, respectively) of 248 and 309 m/min



**Figure 2.** Three example relationships between steady-state heart rate (HR) and roller skiing speed for three subjects: Subject 1:  $\text{HR} = 0.50 \times S + 11.70$  ( $r = 0.98$ ), open circles with short-dashed line; Subject 2:  $\text{HR} = 0.20 \times S + 99.85$  ( $r > 0.99$ ), open squares with long-dashed line; Subject 5:  $\text{HR} = 0.34 \times S + 41.56$  ( $r > 0.99$ ), open diamonds with solid line. Vertical dotted lines correspond to the “slow” and “fast” common speeds (CS1 and CS2, respectively) of 248 and 309 m/min

**Table 3.** Summary of correlations (99% CI) between measures of flexibility and predicted oxygen consumption ( $\text{VO}_2$ , ml/kg/min) and heart rate (HR, BPM) at “slow” (248 m/min) and “fast” (309 m/min) common speeds of roller skiing (n=12)

Flexibility Tests	Common Speed = 248 m/min		Common Speed = 309 m/min	
	Roller skiing		Roller skiing	
	HR	$\text{VO}_2$	HR	$\text{VO}_2$
Right Total Body Rotation	0.38 (-0.43-0.85)	0.48 (-0.32-0.88)	0.15 (-0.61-0.77)	0.38 (-0.43-0.85)
Left Total Body Rotation	0.46 (-0.34-0.88)	0.50 (-0.30-0.89)	0.24 (-0.55-0.80)	0.42 (-0.39-0.86)
Right Lateral Flexion of Lumbar Spine	-0.35 (-0.84-0.46)	0.35 (-0.45-0.84)	-0.40 (-0.86-0.41)	0.29 (-0.51-0.82)
Left Lateral Flexion of Lumbar Spine	-0.16 (-0.77-0.60)	0.25 (-0.54-0.81)	-0.16 (-0.77-0.60)	0.29 (-0.50-0.82)
Shoulder Rotation	0.22 (-0.56-0.80)	-0.46 (-0.88-0.34)	0.42 (-0.39-0.66)	-0.26 (-0.81-0.53)
Right Standing Horizontal Hip Abduction	-0.22 (-0.81-0.54)	0.26 (-0.53-0.81)	-0.21 (-0.79-0.57)	0.27 (-0.52-0.81)
Left Standing Horizontal Hip Abduction	0.02 (-0.68-0.71)	0.50 (-0.30-0.89)	-0.17 (-0.77-0.60)	0.51 (-0.29-0.89)
Right Lying Horizontal Hip Abduction	-0.36 (-0.85-0.44)	0.37 (-0.43-0.85)	-0.38 (-0.85-0.42)	0.11 (-0.64-0.75)
Left Lying Horizontal Hip Abduction	0.02 (-0.68-0.71)	0.26 (-0.53-0.81)	0.03 (-0.68-0.71)	0.21 (-0.57-0.79)
Modified Sit-and-Reach	0.00 (-0.70-0.70)	0.37 (-0.44-0.85)	0.08 (-0.65-0.73)	0.16 (-0.60-0.77)
Right Passive Leg Raise	0.26 (-0.53-0.81)	0.68 (-0.03-0.93)	0.21 (-0.57-0.79)	0.58 (-0.20-0.91)
Left Passive Leg Raise	0.14 (-0.61-0.76)	0.54 (-0.25-0.90)	0.15 (-0.61-0.77)	0.36 (-0.45-0.84)

**Figure 3.** Correlational relationships between steady-state oxygen consumption ( $\text{VO}_2$ ; Graph A) and heart rate (HR; Graph B) slope parameters with shoulder rotation (SR) flexibility (n=12). Least squares derived lines were as follows:  $\text{VO}_2$  Slope =  $0.003 \times \text{SR} + 0.004$  ( $r = 0.49$ ;  $P = 0.11$ ); HR Slope =  $0.005 \times \text{SR} + 0.188$  ( $r = 0.31$ ;  $P = 0.33$ ). Vertical dotted lines correspond to 20<sup>th</sup> percentile ranking for SR within the subject sample tested

The present study results are consistent with previous studies that have found no relationship between measures of flexibility and running E [5, 20]. However, the present study also contradicts the often cited research suggesting that inflexibility of the trunk and lower limbs are associated with enhanced running E [9, 12, 15].

**Observational Measures of Static Flexibility.** The exact degree to which the present study can be compared with the previous running E literature is not clear without a more general discussion of how flexibility has been associated with different types of performance. In addition, some of the contradiction in the running E research literature may relate to a variety of factors that include differences in study methodology, types of stretching and flexibility measures evaluated, as well as the nature of the hypothesized influence of flexibility on performance. First, focusing on the latter issue, the research literature directly relating measures of flexibility with measures of strength/power and endurance performance can be generally classified into three types of studies: 1) Observational measurements of flexibility [5, 9, 12, 15, 27], 2) acute influence of stretching exercises [13, 30], and 3) chronic influence of stretching exercises [16, 20, 21, 29]. Among these classifications, the studies providing the most contradictions are those that have correlated observational measures of static flexibility with measures of E. Craib et al. [9], for example, correlated nine measures of trunk and lower-limb flexibility in 19 male distance runners with running E at 187.8 m/min. Only dorsiflexion ( $r = +0.65$ ) and SHHA ( $r = +0.53$ ) correlated significantly with E, which led to the conclusion that inflexibility within certain regions of the body, such as the hips and ankles, may contribute to an improved running E by assisting with body stabilization during ground impact without a concomitant energy cost. Jones et al. [15] reported an even stronger correlation ( $r = +0.68$ ) between running E at 266.7 m/min for 34 well-trained male distance runners and flexibility assessed with the sit-and-reach test. Using a more diverse subject sample that included 100 non-runners of both genders across a broad age range (18-62 years), Gleim et al. [12] also reported that subjects who were the least flexible for the trunk rotation test and lower-limb turnout were more economical at both walking and running E. Most recently, Trehearn and Buresh [27] reported a very strong correlation ( $+0.83$ ) between running E and sit-and-reach flexibility using different absolute speeds for well-trained men and women distance runners. Thus, all four studies reported that less flexibility was significantly associated with better running E.

According to Beaudoin and Blum [5], however, these observational studies may have incorporated one or more methodological limitations such as lack of treadmill familiarization [9, 12], use of non-runners to study running E [9], as well as the inclusion of both genders in the subjects sample [9, 27]. Additional limitations could include the use of short stages (< 5 mins) for assessing E [12, 27], as well as the inclusion of too few flexibility measures [15, 27]. In response to these observations, Beaudoin and Blum [5] evaluated the correlations between running E at 160.8 m/min

for 17 female collegiate track and field athletes with six measures of trunk and lower-limb flexibility tests. Interestingly, the authors concluded that there was no strong association between measures of flexibility and running E in collegiate female track and field athletes. This latter study, however, seems to have its own limitations that include use of a relatively slow running speed for evaluating E, the sole use of women as subjects, as well as a lack of detail regarding the actual running background of their subjects. For example, the range of running E values reported by Beaudoin and Blum [5] was 17.8%, while the ranges reported by both Craib et al. [9] and Jones [15] of 19.9% and 22.6%, respectively, were greater using male runners and higher running speeds (187.8- 266.7 m/min).

**Running Versus Roller Skiing E.** Given the review above, the present study seems most similar to Craib et al. [9] and Jones [15] in the use of males for testing, use of well-trained endurance athletes who were very familiar with the mode of testing (i.e., roller skiing), the use of 10-min stages for assessing  $\text{VO}_2$  and HR, as well as the inclusion of E variables that incorporated both slow and fast roller skiing. Despite these similarities, the present study found no significant correlations whereas both Craib et al. [9] and Jones [15] reported significant correlations. This suggests that static flexibility is less of a determinant of skate roller skiing E than for running E. There are several possible explanations for this observation. First, cross-country skiing performance is generally considered to be much more skill dependent than distance running which could imply that skiing E is more dependent upon skill itself than specific or regional measures of flexibility. Modern skate skiing, for example, has been described as having seven kinematically unique techniques [3], all of which can be relied upon during a single ski race. It has also been shown that the skillful use of these skate skiing techniques will vary with the incline of the terrain, the speed of movement, as well as the caliber of athlete [3, 18]. Of course, the application of these skating techniques when skiing on snow will also vary with the snow conditions, the choice of skis, and the final wax preparation of those skis. Thus, the modern skate style of skiing has numerous unique characteristics not found in the sport of running that may influence any underlying relationships between skate roller skiing E and measures of flexibility as evaluated by the present study.

A second possible explanation is that the hypothesized mechanisms underlying significant correlations between flexibility and running E may not be the same as for roller skiing E. Several authors have suggested, for example, that less flexible musculotendinous structures may act to stabilize the pelvic region especially during foot impacts with the ground while running [9, 12, 15]. These "tight" structures may serve to passively support the pelvic region and thus improve running E by decreasing the total metabolic demand of running. The lower body musculature during skate skiing, in contrast, does not experience nearly as high of ground impact forces as during running. Thus, passive support of the pelvic region during ground impact is probably less



important to minimizing roller skiing E than that for running E.

**Upper Body Contributions to Skiing.** Given that total power generation for skate skiing involves contributions from the upper and lower body, as well as the poor correlation of roller skiing E with sit-and-reach scores (traditional correlate of running E), the focus of this discussion should be redirected toward upper body flexibility and established correlates of performance. Indeed, many recent studies have focused on the double-poling motion of the upper body which is a common poling strategy amongst many skating and classic techniques [2]. For example, measures of double-poling upper body power (UBP) from short duration (<60 secs) maximal efforts has been shown to correlate very highly ( $r=0.92-0.93$ ) with 10 km classic skiing performance [2]. In another study, the actions of the muscles crossing the elbow and shoulder joints during high force double-poling were shown to be consistent with stretch-shortening cycling (SSC) contractions [19]. According to Komi [17], an effective SSC action involves the effective storage and release of elastic energy first generated during a high force eccentric contraction and then released during a subsequent concentric contraction of the same muscle or muscle group. In fact, the generation of upper body power during the double poling motion (which is essentially the same upper body motion used for both the techniques used in the present study) has been described as critically dependent upon the proper use of the SSC [25]. It has been suggested that the combination of SSC actions at the shoulder and elbow joints are timed to allow for ski pole forces to provide maximal forward propulsive forces [19,25]. Thus, a focus on the high force double-poling motion of the upper body, which is common to many cross-country skiing techniques, may be an appropriate focus for future skiing studies rather than measures of E.

It has been hypothesized that increased musculotendinous stiffness is beneficial to muscle contractions that emphasize an SSC, while the same stiffness may be detrimental to isometric and concentric contractions [30]. According to a review by Shrier [24], virtually all studies investigating the influence of an acute bout of static stretching on strength and power performances (e.g., dependent measures including maximal voluntary contraction, power, jump height, jump force, and jump velocity) reported diminished performances. Young and Elliot [30], for example, found that drop jump performance decreased significantly when preceded with an acute bout of static stretching. The authors speculated that acute static stretching functioned to decrease musculotendinous stiffness which, in turn, decreased SSC performance capacity. In contrast, the same study found that the same acute bout of static stretching did not influence squat jump performance which emphasized concentric explosive muscular contractions. Interestingly, plyometric training has been found to increase both musculotendinous stiffness and SSC dependent measures of performance (i.e., counter movement jump height, 5-bound jump test) while improving running E in trained distance runners [26]. Thus,

while chronic lower body plyometric training can increase musculotendinous stiffness and improve running E, acute static stretching is hypothesized to decrease musculotendinous stiffness and negatively impact SSC dependent muscular performances.

The common factor among the studies described above is their dependence upon the SSC for performance. Unfortunately, the present study was not able to collect measures during high force double-poling on a treadmill [19], or even short duration measures of upper body power [2], both of which appear to be better models for evaluating skiing-specific SSC dependent muscular contractions. The present study did have some interesting observations, however, that may relate to this discussion. When compared with appropriate age and gender matched normative categories, seven of the 12 subjects had TBR test scores  $\leq$  the 20<sup>th</sup> percentile [14]. Similarly, nine of the 12 subjects had SR scores that ranked in the 20<sup>th</sup> percentile or lower [14]. While the SR test emphasizes flexibility of the glenohumeral joint and shoulder girdle in the frontal plane, the TBR measures flexibility in the transverse plane and includes flexibility of the glenohumeral joint, the thoracic and lumbar spine, the pelvis, as well as the knee and ankle joints. Based upon feedback from subjects during testing, glenohumeral joint tightness subjectively impacted the scores for both tests the most. Thus, at the very least, low flexibility in the shoulder region does not appear to be a detriment to skate skiing performance. In fact, an inflexible shoulder joint/girdle may aid in the transfer of force to the ski poles by utilizing stored elastic energy which, in turn, could result in a decreased energy cost (i.e., enhanced SSC utilization via increased musculotendinous stiffness which leads to improved E) of skiing. If this were true, the lack of significant correlations between these measures of upper body flexibility (i.e., TBR and SR) and roller skiing E could be explained by most subjects having similarly low flexibility scores.

## 5. Conclusions

The present study describes the correlational relationships between multiple measures of flexibility and skate roller skiing economy. As such, this study should be viewed as a starting point for understanding these relationships. This study's lack of significant relationships may indicate that neither high nor low flexibility is a prerequisite to minimizing the submaximal energy cost of skate roller skiing as evaluated in this study. This interpretation, however, may be dependent upon the choice of skate skiing techniques (G3 and G4), the ability of the skiers to perform the skating technique, testing terrain (level track), the population of skiers evaluated (trained collegiate males), or even the dependent measure (roller skiing E) used in the present study. Future research with flexibility and skiing should probably focus on the high intensity double-poling motion of the upper body, a motion that is common to many skiing techniques. Such an experimental model would maximize the dependence of the double-poling upper motion on SSC

contractions. Lastly, given the homogeneity of the subjects tested by this study (i.e., Male collegiate cross-country skiers), future studies may focus on elite skiers where small differences in E are likely to be more important to skiing performance than for lower caliber athletes.

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## REFERENCES

- [1] Alricsson, M, Harms-Ringdahl, K, Eriksson, K, Werner S. The effect of dance training on joint mobility, muscle flexibility, speed and agility in young cross-country skiers - a prospective controlled intervention study. *Scan J Med Sci Sports* 2003; 13: 237-243.
- [2] Alsobrook NG, Heil DP. Anaerobic and aerobic upper body power as determinants of classical cross-country ski performance. *Eur J ApplPhysiol* 2009; 105:633-641.
- [3] Andersson E, Supej M, Sandbakk O, Sperlich B, Stoggl T, Holmberg HC. Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur J Appl Physiol* 2010; 110(3): 585-595.
- [4] Baumgartner TA, Jackson AS. *Measurement for Evaluation in Physical Education and Exercise Science* (5<sup>th</sup>ed). Brown & Benchmark Publishers, Madison, WI:1995.
- [5] Beaudoin CM, Blum JW. Flexibility and running economy in female collegiate track athletes. *J Sports Med Phys Fitness* 2005; 45(3): 295-300.
- [6] Cavanagh PR, Kram R. The efficiency of Human movement – a statement of the problem. *Med Sci Sports Exerc* 1985; 17(3): 304-308.
- [7] Cohen J. *Statistical power analysis for the behavioral sciences* (2<sup>nd</sup>ed). Erlbaum, Hillsdale, NJ 1988.
- [8] Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc* 1980; 12(5): 357-360.
- [9] Craib MW, Mitchell VA, Fields KB, Cooper TR, Hopewell R, Morgan DW. The association between flexibility and running economy in sub-elite male distance runners. *Med Sci Sports Exerc* 1996; 28(6): 737-743.
- [10] Daniels J, Daniels N. Running economy of elite male and elite female runners. *Med Sci Sports Exerc* 1992; 24(4): 483-489.
- [11] Gleim GW, McHugh MP. Flexibility and its effects on sports injury and performance. *Sports Med* 1997; 24(5): 289-299.
- [12] Gleim GW, Stachenfeld NS, Nicholas JA. The influence of flexibility on the economy of walking and jogging. *J Orthop Res* 1990; 8: 814-823.
- [13] Godges JJ, MacRae H, Longdon C, Tinberg C, MacRae P. The effects of two stretching procedures on hip range of motion and gait economy. *J Orthop Sports PhysTher* 1989; 7: 350-357.
- [14] Hoeger WWK, Hoeger SA. *Fitness and Wellness*. Thomson Wadsworth, Belmont, CA 2006.
- [15] Jones AM. Running economy is negatively related to sit-and-reach test performance in international-standard distance runners. *Int J Sports Med* 2002; 23: 40-43.
- [16] Kokkonen J, Nelson AG, Eldredge C, Winchester JB. Chronic static stretching improves exercise performance. *Med Sci Sports Exerc* 2007; 39(10): 1825-1831.
- [17] Komi PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech* 2000; 33: 1197-1206.
- [18] Kvamme B, Jakobsen V, Hetland S, Smith G. Ski skating technique and physiological responses across slopes and speeds. *Eur J ApplPhysiol* 2005; 95: 205-212.
- [19] Lindinger SJ, Holmberg HC, Müller E, Rapp W. Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing. *Eur J ApplPhysiol* 2009; 106: 353-363.
- [20] Nelson AG, Kokkonen J, Eldredge C, Cornwell A, Glickman-Weiss E. Chronic stretching and running economy. *Scan J Med Sci Sports* 2001; 11: 260-265.
- [21] Nelson AG, Kokkonen J, Eldredge C. Strength inhibition following an acute stretch is not limited to novice stretchers. *Res Q Exerc Sports* 2005; 76(4): 500-506.
- [22] Nilsson J, Tveit P, Eikregagen O. Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biom* 2004; 3(1): 85-108.
- [23] Rusko H. Physiology of cross-country skiing. *In Handbook of sports medicine and science – cross-country skiing. Edited by H. Rusko. Blackwell Publishing Company* 2003: pp. 1-31.
- [24] Shrier I. Does stretching improve performance? A systematic and critical review of the literature. *Clin. J. Sport Med* 2004; 14(5): 267-273.
- [25] Smith GA. Biomechanics of cross-country skiing. *In Handbook of sports medicine and science – cross-country skiing. Edited by H. Rusko. Blackwell Publishing Company* 2003: pp. 32-61.
- [26] Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. *Eur J ApplPhysiol* 2003; 89: 1-7.
- [27] Trehearn TL, Buress RJ. Sit-and-reach flexibility and running economy of men and women collegiate distance runners. *J Strength Cond Res* 2009; 23(1): 158-162.
- [28] Turner AM, Owings M, Schwane JA. Improvement in running economy after 6 weeks of plyometric training. *J Strength Cond Res* 2003; 17(1): 60-67.
- [29] Wilson GJ, Elliott BC, Wood GA. Stretch shorten cycle performance enhancement through flexibility training. *Med Sci Sports Exerc* 1992; 24(1): 116-123.
- [30] Young W, Elliott S. Acute effects of static stretching, proprioceptive neuromuscular facilitation stretching, and maximum voluntary contractions on explosive force production and jumping performance. *Res Q Exerc Sports* 2001; 72(3): 273-279.