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Maximal strength in upper-body segments as determinants of power output in double poling among well-trained female cross-country skiers

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Abstract

The aim of the present study was to analyze how maximal strength in the elbow, shoulder, and trunk segments influence double poling efficiency and power output among well-trained female cross-country skiers. In addition, double poling technique and body composition was analyzed. Thirteen well-trained female cross-country skiers (age 22±3 yrs, body mass 61±5 kg, VO_{2max} running 65±4 $ml \cdot kg^{-1} \cdot min^{-1}$) were tested for maximal strength (1RM) in elbow and shoulder extension, and trunk flexion exercises. Double poling was performed using a Concept2 SkiErg poling ergometer where the skiers completed three 4-min submaximal stages, as well as a 3-minute and 30-second all-out tests. Work rate and cycle rate were measured with the ergometer's internal software. Average power output determined performance in the 3-minute and 30-second all-out tests, whereas gross efficiency was estimated at 90 W. Body composition was measured using dual-energy X-ray absorptiometry. Both the power output in the 30-sec test and the 3-min test showed significant correlations with 1RM in elbow, shoulder and trunk (30-sec: r=0.85, 0.88, 0.64, all P<0.001; 3-min: r=0.54, 0.58, 0.66, all P<0.05). Gross efficiency only correlated significantly with trunk 1RM only (r=0.55, P=0.03). Stepwise multiple regression analysis revealed that 1RM of the elbow and shoulder together were the best predictors of 30-sec performance (R^2=0.88,) and that 1 RM of the trunk alone was the best predictor of 3-min performance (R^2=0.39). The average work per cycle during the 30-sec test showed significant correlations with all strength tests (r=0.61-0.85, P<0.05), while no significant correlations were found between the strength tests and work per cycle in the 3-min test. Total, arm and trunk lean body mass correlated all with the 1RM strength and performance tests (r=0.55-0.87, all P<0.01). This study demonstrates that the impact of maximal strength in elbow and shoulder segments increase with increasing demands of power production, whereas maximal trunk strength has a similar importance for poling efficiency and power output across all intensities. Since both power output in double poling and maximal strength were associated with high lean body mass in arms and trunk, enhanced upper-body muscle mass may be advantageous for female skiers.

Key words: isolated strength, performance, women.

Abstrakt

Denne studien hadde som formål å undersøke påvirkning av maksimal styrke i overkroppssegmenter på mekanisk effektivitet, i tillegg til kraftutviklingen i staking på 30-sekunder og 3-minutters test for godt trente kvinnelige langrennsløpere. For å gi ytterligere innsikt i disse mekanismene ble staketeknikk og kroppssammensetning analysert. Tretten veltrente kvinnelige langrennsløpere (alder 22±3 år, kroppsmasse 61±5 kg, VO_{2max} 65±4 ml/kg/min) testet maksimal styrke (1RM) i albue ekstensjon, skulder ekstensjon og trunk fleksjon. Staking ble utført på en Concept2 SkiErg poling ergometer der skiløperne fullførte tre submaksimale drag på fire minutter, samt 3-minutter og 30-sekunders test til utmattelse. Arbeidskapasitet og frekvens ble målt med ergometerets interne programvare. Gjennomsnittlig watt bestemte prestasjonen, mens mekanisk effektivitet ble beregnet som ytre arbeid dividert på indre arbeid, og ble interpolert på 90 W for alle deltagerne. Kroppssammensetning ble målt ved hjelp av dual-energy X-ray absorptiometry. Både kraftutviklingen på 30-sekunder testen og på 3-minutter testen viste signifikant korrelasjon med 1RM i albue, skulder og mage segmentet (30-sekunder r = 0,85, 0,88, 0,64, alle P < 0,001, 3-minutter r=0,54-0,58, 0,66, alt P=0,05). Mekanisk effektivitet interpolert på 90W korrelerte bare signifikant med 1RM i magesegmentet (r=0,55,P=0,03). Stegvis multippel regresjonsanalyse avdekket at 1RM av albue og skuldersegmentene sammen var de som best predikerte kraftutviklingen på 30-sekunder testen (R2=0,88) og at 1RM av magesegmentet alene var det segmentet som best predikerte kraftutviklingen på 3-minutter testen (R2 = 0,39). Det gjennomsnittlige arbeidet produsert per syklus i løpet av 30-sekunder testen viste signifikante korrelasjoner med alle styrketestene (r=0,61 til 0,85, P<0,05), men ikke gjennomsnittlig arbeid produsert per syklus i løpet av 3-minutter testen. Andelen fettfri masse i arm og mage korrelerte høyt med både 1RM styrketestene og kraftutviklingen på stakingen (r=0,55 til 0,87, alle P<0,01). Denne studien viser at virkningen av maksimal styrke i albue og skulder segmentene øker med økende krav til ytre arbeid, mens maksimal magestyrke har en lignende betydning for både mekanisk effektivitet og prestasjonene på tvers av intensiteter. Siden både stakeprestasjon og maksimal styrke var assosiert med høy fettfrimasse i armer og mage, kan høyere muskelmasse i overkroppen være en fordel for kvinnelige skiløpere.

Nøkkelord: isolert, prestasjon, damer

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Cross-country skiing is an endurance sport where the whole body contributes to forward propulsion through a combination of upper body poling and leg push-offs (Sandbakk & Holmberg, 2014) . Previous studies have shown that cross-country skiing is one of the most demanding endurance sports and that professional skiers are among the athletes with the highest maximal oxygen uptake (Holmberg, Rosdahl & Svedenhag, 2007; Saltin & Astrand, 1967). Through the past few decades the sport has developed with greater attainable racing speeds as a consequence of better prepared tracks and more functional equipment (Saltin, 1997; Sandbakk & Holmberg, 2014). The introduction of both the mass start and sprint competitions has further increased the importance of creating higher speeds in parts of the race (Sandbakk & Holmberg, 2014). Consequently, physical factors associated with the increased race speed, such as muscular strength, have become of increasing importance for skiing efficiency and performance.

The increased race speed in the classical part of cross-country skiing has led to more use of the double poling technique, especially in the sprint and mass start competitions (Stöggl et al. 2006; Holmberg 2005). The increased use of the double poling technique has contributed to greater importance of the upper body to produce effective poling that interacts with active leg-work in the double poling movement (Holmberg, Lindinger, Stoggl, Bjorklund & Muller, 2006; Holmberg, Lindinger, Stoggl, Eitzlmair & Muller, 2005). Following, these developments in the double poling movement have led to higher poling forces, shorter contact times with longer recovery times, and longer cycle lengths (Holmberg et al., 2006; Holmberg et al., 2005; Stoggl, Muller, Ainegren & Holmberg, 2011). Thereby, these changes in the double poling technique, together with increased demands from higher racing speeds, has increased the importance of both upper body endurance and strength capacity (Alsobrook & Heil, 2009; Heil, Engen & Higginson, 2004; Mahood, Kenefick, Kertzer & Quinn, 2001; Nilsson, Holmberg, Tveit & Hallen, 2004; Sandbakk & Holmberg, 2014).

Previous studies have shown maximal upper body strength to be of importance for double poling performance (Hoff, Helgerud & Wisloff, 1999; Osteras, Helgerud & Hoff, 2002; Stoggl, Lindinger & Muller, 2007a, 2007b; Stoggl et al., 2011). However, the influence of maximal strength reaches a plateau, when other physiological factors become of greater importance (Stone, 2002). This suggests that an increase in maximal strength is not always beneficial for the performance (Losnegard et al., 2011; Sandbakk, Holmberg Leirdal, & Ettema, 2010; Stoggl et al., 2011), though the link between maximal upper body strength and performance in double pooling seems especially high among female skiers (Hoff et al., 1999; Losnegard et al., 2011). This may be explained by the fact that females in absolute terms are weaker in their upper body than males, and thereby, upper body strength becomes a more limiting factor for the performance among females. These findings are also supported by examinations of other sports showing that maximal strength has a greater influence on the power output when the resistance increases (Stone, 2002).

To date no study has investigated the influence of maximal strength in the upper body segments on double poling performance at different work rates, even though the contribution from elbow, and shoulder extension, and trunk flexion muscles and their activation patterns are known to alter with increasing work rate (Holmberg et al., 2005; Lindinger, Holmberg, Muller & Rapp, 2009). More specifically Holmberg et al. (2005) reported high activation levels of muscles attached to the shoulder and trunk segment at 85% of maximal poling velocities, and Lindinger et al. (2009) found a rapid increase in muscle activation as the work rate increased in muscles attached to the shoulder and elbow segments. However, a further investigation of how strength in the different upper body segments influences the double poling performance is required.

The aim of the present study was to analyze how maximal strength in the elbow, shoulder, and trunk segments, measured in isolation, influence double poling efficiency and power output among well-trained female cross-country skiers. To provide further insight into the mechanisms related to these possible associations, poling technique and body composition was analyzed. It was hypothesized that maximal strength in all exercises would correlate with efficiency and power output in double poling and, further, that the importance of shoulder and elbow strength for power output would increase at higher double poling intensity.

Methods

Participants

Thirteen well-trained female cross-country skiers volunteered to participate in the study. The participants could be classified within a range from talented junior skiers to nationally ranked senior skiers. The participants' performance level on snow according to the FIS-point system, anthropometrics and physiological characteristics are shown in Table 1. All skiers were fully acquainted with the nature of the study before signing written consent to participate. The study was approved by the Regional Ethics Committee, Trondheim, Norway.

Table 1. Anthropometrics, physiological characteristics and performance level (FIS-points) of the 13 female skiers involved in this study (mean ± SD).

	Parameters
Age (years)	22.7 ± 3.7
Body Height (cm)	168.5 ± 5.2
Body mass (kg)	61.9 ± 5.4
$VO_{2\ peak}$ Double poling (mL·kg^{-1}·min^{-1})	54.0 ± 2.4
$VO_{2\ max}$ running (mL·kg^{-1}·min^{-1})	64.9 ± 4.2
FIS-points	107 ± 25

$VO_{2peak=}$ Double poling in a ski ergometer

The experimental design

The present study determined the influence of maximal strength in different upper body segments upon efficiency and power output in double poling by using a cross-sectional design. 1RM was performed in poling-specific strength exercises simulating an elbow extension, shoulder extension and trunk flexion. Thereafter, ventilatory responses, work rate and cycle characteristics during three different submaximal stages at increasing intensities were measured while double poling on a SkiErg poling ergometer. The same measurement and exercise mode were assessed during a 30-second and a 3-minute all-out test. Running VO_{2max} was also measured by up-hill running at a constant inclination of 10.5% and with increasing speed on a motorized treadmill to examine the participant's maximal aerobic capacity.

Instruments and materials

The elbow extension exercise was performed while sitting on a curl-bench next to a multi cable apparatus (Beach Mountain AS, Norway) with a custom handlebar attached to the grip (Figure 2). The shoulder extension was performed sitting on an adjustable bench (Beach Mountain AS, Norway) using the same multi cable apparatus and the same handlebar as in the elbow extension (Figure 3). The trunk flexion exercise was performed in an abdominal machine (PF-600G, Beach Mountain AS, Trondheim Norway) (Figure 4). Both the cable apparatus and the abdominal machine were checked and corrected for friction, and had a constant friction with increasing weight resistant. The friction measurement was performed with a force cell mounted at the end of the cable apparatus next to the handlebar (Noraxon U.S.A. inc, Scottsdale, Arizona, US).

Simulated double poling was performed in a modified Concept2 SkiErg (Morrisville, Vermont, US), with resistance level-1. Ventilatory variables were measured by the Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). Prior to each measurement, the VO_2 and VCO_2 analysers were calibrated using a known mixture of gases, 16.00 ± 0.04% O_2 and 5.00 ± 0.1% CO_2 (Riessner-Gase Gmb H & Co Lichtenfels, Germany) and the expiratory flow meter was calibrated with a 3-L syringe (Hans Rudolph Inc., Kansas City, MO). Heart rate was measured using a Suunto t6c heart rate monitor (Suunto oy, Vantaa, Finland). Blood lactate values were obtained from a 20µl blood sample collected from the fingertip and analysed using a Biosen C_line Sport lactate analyser (EKF-diagnostic GmbH, Barleben, Germany). Movement characteristics were recorded with seven infrared Oqus cameras (Qualisys AB, Gothenburg, Sweden). Four reflective markers were placed on the poling ergometer and one marker was placed on each pulling rope and handlebar.

Body composition in terms of total mass, lean mass, fat and bone were analyzed for the whole body, trunk and arms using the DXA software (Encore 2007, Version 11.4, General electric Company, Madison, USA). The equipment was calibrated before each measurement using a phantom and according to the manufacturer’s guidelines. Total mass and lean mass values for the whole body, trunk and arms are presented as absolute values. Qualified personnel at the St. Olavs Hospital in Trondheim conducted DXA scan measurements.

Test protocols and measurement

Strength tests

In following order, the elbow extension, shoulder flexion, and trunk flexion exercises were used to test 1RM strength in the different upper body segments. Prior to testing, the participants performed a 10 min warm-up running on a treadmill at low intensity and four movement specific warm up sets with gradually increasing load. Based on Kraemer, Ratamess, Fry, and French (2006), 2 times 10 repetitions at 40% of 1RM, 5 repetition at 60% of 1RM, and 3 repetitions at 85% of the respective 1RM were performed. Two extra sets with 10 repetitions at 40% of the 1RM were added to be sure that the participants were familiar with the test exercises before testing. First, one 1RM attempt was performed 2.5kg below the expected 1RM. The weight was then further increased by 1.25 to 5.00 kg until the participant failed to lift the load correctly. The same researcher supervised all strength tests, and gave the subjects verbal feedback to ensure good technique throughout lifting. All tests were performed on the same day within an hour, and all skiers were familiar with the test-exercises by using similar exercises as part of their regular training and testing regime.

The elbow extension exercise is shown in Figure 1. The lift started when the angle between humerus and ulna/radius was less than 90 degrees, and finished when either the underarm hit the bench or the elbow joint was fully extended. The participants were sitting in a curl-bench and strapped over the forearm to better isolate the movement.

Figure 1. Picture series of the elbow extension exercise from start to end position.

The shoulder extension exercise is shown in Figure 2. A seated bench was positioned perpendicular to the apparatus so that the bar was pulled vertically down to the chest region. The back on the bench was adjusted in an upright position, approximately to 80 degrees. To limit the movement from other body segments and create stability during the lift, participants were strapped to the bench over the hip and chest region. The lift started with straight arms above the head, and finished when the handlebar reached the lower chest region.

Figure 2. Picture series of the trunk extension exercise from start to end position.

The trunk flexion exercise is shown in Figure 3. Each participant had the handlebar placed at shoulder-height, and the lift was completed when the top of the handlebar hit or passed the leg.

Figure 3. Picture series of the trunk flexion exercise from start to ending possession.

Double poling modes in the ski ergometer

The entire double poling test protocol is shown in Figure 4. Prior to the submaximal poling tests, the skiers performed a 10 min low-intensity warm-up running on a treadmill at low intensity, followed by 5 minute double poling at approximately 60% of maximal heart rate. Submaximal testing consisted of three 4-minute stages with double poling performed on the SkiErg poling ergometer. Between the sessions a two-minute rest period was applied and immediately after each submaximal stage blood lactate was obtained. The intensity was adjusted by a subjective fatigue scaling ranging from 6-20, were 6 indicates no effort and 20 indicated maximal effort (Borg 1982). In this study the intensity on the submaximal stages was set to 9, 13 and 15 on the Borg scale, representing low, moderate and high submaximal intensity respectively (Borg, 1982). Ventilatory responses, work rate, and cycle characteristics were measured during all the submaximal tests and the last minutes measures were used for further analyses.

After the submaximal poling test, a rest period of 5 minute was applied before the 30-second all-out modified Wingate test was performed. In the last minute of the rest period the participants were allowed to double pole at a low intensity to enhance recovery. Throughout the 30-seconds the participants were encouraged to perform with maximal effort. The average power output during the 30-seconds test determined performance.

After the 30-second all-out test another 10 minute rest period was applied. Also for this rest period the participants were allowed to double pole at low intensity to enhance recovery. During this test the participants were encouraged to perform maximally, but with some pacing advice based on the work rate obtained at the submaximal tests. The average power output during the 3 minutes determined performance. VO_2 was measured continuously during the entire 3-minute all-out test and the three highest consecutive 10-second values determined VO_2peak.

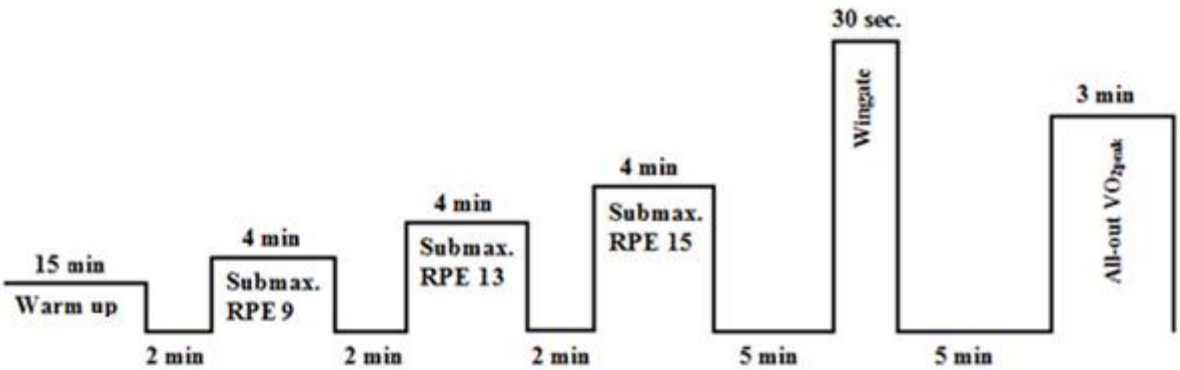

Figure 4. The entire double poling testing protocol performed in the SkiErg. All subjects completed a 10-min warm up on the treadmill (running) with 5 minute specific warm-up in the SkiErg. This was followed by three submaximal workloads at 9, 13 and 15 RPE, a 30-second all-out test and a final 3-minute all-out test.

Figure 5. Shows double poling mode on the SkiErg poling ergometer.

Performance level on snow

The performance level on snow was based on the FIS point system. According to FIS, a skier's rank is set relative to a zero-point standard, established by the top-ranked skier in the world, where better skiers have fewer FIS points. A skier's total score for a given race is determined by adding race points from comparing the individual ski time to the winner's time and adding racing penalties. For this study the FIS points were calculated based on the mean of the two best races during a two months period after the tests.

$VO_{2\,max}$ running test

After a 10 minute warm-up running on a motorized treadmill the $VO_{2\,max}$ test was performed according to standardized procedures for testing cross-country skiers in Norway (Ingjer, 1992). The test lasted for 5 to -6 minutes and was performed running uphill at a constant inclination of 10.5% with individual starting speeds and a gradual increase of 1km $\cdot$/h^{-1} every minute. The maximal level of effort was reached when a plateau in VO_2 was achieved, despite increasing intensity of exercise, and a peak BLa > 8 mmol·l occurred

(Basset & Howley, 2000). VO_2 was monitored continuously and VO_{2max} was determined as the average of the highest three consecutive 10-second intervals.

Calculations

Mechanical power, work rate and cycle rate were measured with the ergometer's internal software, which had been validated with force velocity measurements, and against the average power output during the 30-second and 3-minute all-out tests determined upper body poling performance. Work per cycle was calculated as the mechanical power divided by cycle rate.

The metabolic rate was calculated as the product of VO_2 and oxygen energetic equivalent, and processed using a standard conversion table according to Perronet and Massicotte (1991). Gross efficiency was calculated by dividing work rate on metabolic rate, and expressed as a percentage. Since gross efficiency depends on work rate (Sandbakk et al., 2010), the gross efficiency was interpolated at 90 watts (GE_{90W}) in order to compare skiers at the same work rate.

Statistical analyses

All data were checked for normality with the Shapiro-Wilks test and by calculating Z-scores for skewness and kurtosis. The Z-scores varied between -0.95 and 1.67 and -1.34 and 0.94 for skewness and kurtosis, respectively. Data are presented as mean and standard deviations (SD). Correlations between variables were analyzed using Pearson's correlation coefficient and simple linear regression was used to draw trend lines. Correlation coefficients were interpreted according to Hopkins et al. (2009) as follows; $r < 0.1$ = trivial, 0.1-0.3 = small, 0.3-0.5 = moderate, 0.5-0.7 = large, 0.7-0.9 = very large, 0.9-1.0 = nearly perfect, and 1.0 = perfect. Paired t-test was used to analyses significant differences between the three submaximal stages, as well as work per cycle and cycle rate between the 30-second and 3-minute tests respectively. Stepwise multiple regressions were employed to predict performance from the strength tests. Data were checked for collinearity and heteroscedasticity by plotting the individual variables against each other and calculating the bivariate correlation between each pair of variables. Statistical significance was set at $P < 0.05$. All analyses were performed using SPSS version 21.0 (SPSS, Inc., Chicago, IL).

Results

Relationship between power output in double poling on the SkiErg poling ergometer and performance level on snow

Skiers had 107 ± 25 FIS-points. The average power output produced in the SkiErg was 195 ± 35 W and 145.3 ± 28 W for the 30-second and 3-minute all-out tests respectively. The skiers FIS-points did not significantly correlate with the power output produced in the 30-second all-out test ($r = 0.47$ $p = 0.09$), whereas a very large correlation was found between the FIS-points and the power output produced in the 3-minute all-out test (3-minute; $r = 0.83$ $p \leq 0.001$). Gross efficiency showed a very large correlation with the FIS-points ($r = 0.88$; $p \leq 0.001$)

Relationship between maximal strength and power output in double poling

Skiers performed 30.3 ± 3.8 kg in the elbow extension, 43.4 ± 7.0 kg in the shoulder extension and 65.0 ± 7.0 kg in the trunk flexion exercises. Moreover, $VO_{2,}$ respiratory exchange (RER), blood lactate and metabolic rate increased gradually over the three submaximal stages (Table 2). The GE_{90W} was on average 11.8 ± 1.2% (Figure 6). The average work per cycle performed in the SkiErg poling ergometer did not significantly differ between the 30-second and the 3-minute all-out tests (153 ± 24 W versus 148 ± 27 W, $P = 0.66$). However, there was a significant difference in cycle rate between the 30-second and the 3-minutes all-out tests (1.27 ± 0.08 versus 0.98 ± 0.07, $P \leq 0.001$).

Table 2. Physiological responses in 13 well-trained female cross-country skiers during three different submaximal double poling stages in the SkiErg (mean and SD).

	Submax. 1	Submax. 2	Submax. 3
VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	27.8 ± 2.6*	34.5 ± 3.6*	42.5 ± 3.7$^{\$}$
Respiratory exchange ratio	0.94 ± 0.03*	0.96 ± 0.03*	0.99 ± 0.04$^{\$}$
Blood lactate (mmol L^{-1})	2.65 ± 1.02*	3.84 ± 1.42*	6.03 ± 1.59$^{\$}$
Metabolic rate (W)	596 ± 77*	743 ± 94*	921 ± 118$^{\$}$

Submax. 1 = exercise at 9RPE, Submax 2 = exercise at 13RPE, Submax = Exercise at 15RPE.

* = Significant different from previous variable.

$^{\$}$ = Significant different from first variable.

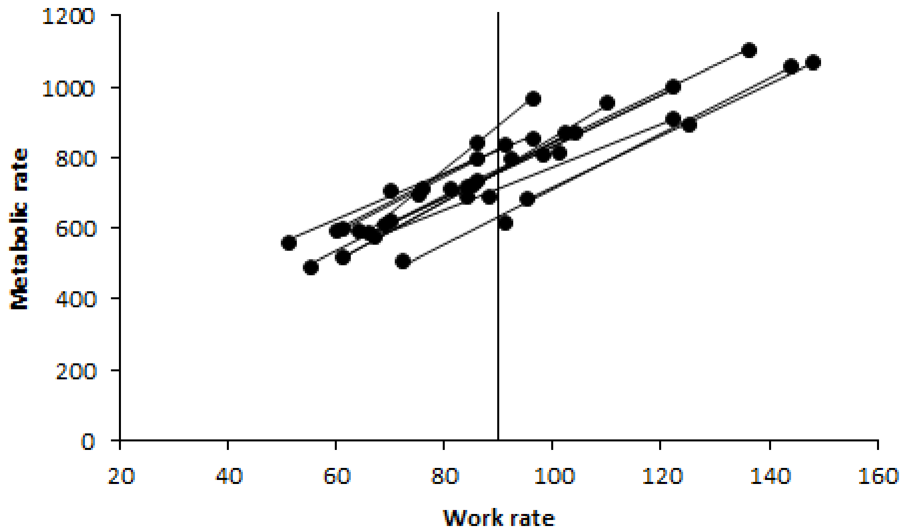

Figure 6. Metabolic rate shown for 13 participants at different work rates during three submaximal stages, with a vertical line placed where the gross efficiency where interpolated. Regression lines are plotted for each participant.

Figure 7 shows maximal strength correlated with the power output produced in the 30-second and 3-minute all-out tests in each isolated upper body segment (shoulder, elbow and trunk); with large to very large correlation seen for the 30-second all-out test ($r = 0.64 – 0.88$, $p = < 0.001 – 0.01$) and for the 3-minute all-out test ($r = 0.54 – 0.66$, $p = 0.03 – 0.01$). However, only the maximal strength in the trunk segment correlated significantly with GE_{90W} ($r = 0.55$, $p = 0.03$).

A stepwise multiple regression analysis employing the average power output, was performed with the 30-second all-out test as the dependent variable and 1RM in the shoulder, elbow, and trunk as the independent variables, and revealed that the 1RM shoulder and 1RM elbow strength in combination provided the best prediction for this test (Adjusted $R^2 = 0.883$, $F = 46.175$, $p < 0.001$). Furthermore, standardized coefficients of 0.481 ($t = 3.683$, $p = 0.002$) for elbow and 0.564 ($t = 4.319$, $p = 0.002$) for shoulder were identified. The stepwise analyses revealed that the 1RM trunk strength was the best predictor when the 3-minute all-out test was employed as an independent variable, and 1RM shoulder, elbow, and trunk strength test were used as independent variables (Adjusted $R^2 = 0.391$, $p = 0.01$), with a standardized coefficient of 0.664 ($t = 2.948$, $p = 0.01$). None of the strength test significantly predicted with GE_{90W}.

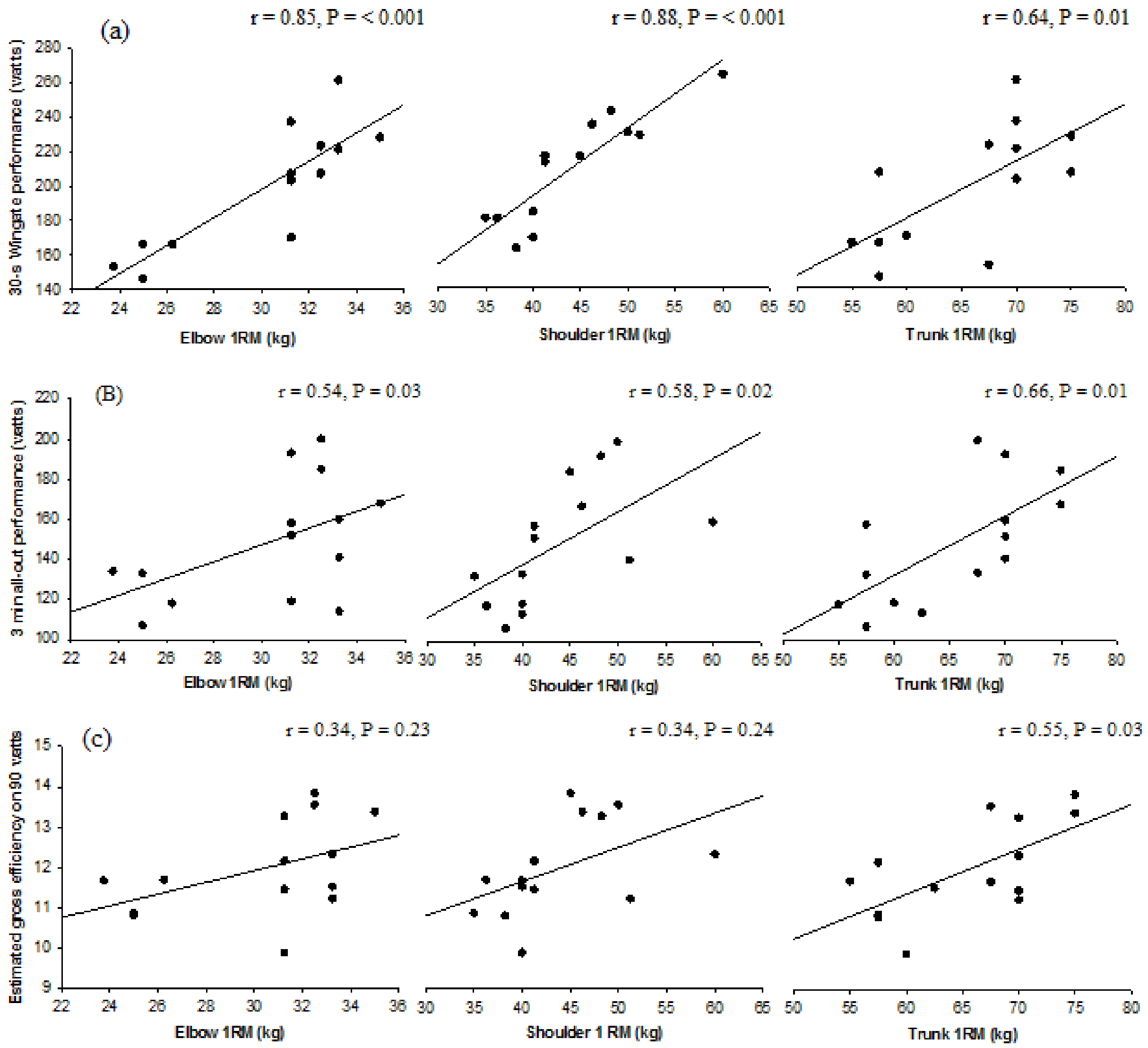

Figure 7. Average power-output produced in the 30second test (a), 3-minute (b) and GE_{90W} (c) plotted against maximal strength test (elbow, shoulder and trunk) shown for the 13participants in this study.

Work per cycle in the 30-second all-out test showed large correlations with the maximal strength in all of the upper body segments ($r = 0.61 - 0.85$, $p < 0.02$), while the correlation between the 3-minute all-out test and the strength tests were not significant ($r = 0.40 - 0.48$, $p < 0.16$). Only the maximal trunk strength and the cycle rate at the 3-minute all-out test showed significant correlation ($r = 0.74$, $p = 0.1$).

Relationships between body compositions, maximal strength and power output in double poling

Total body mass for the participants in this study was 62.5 ± 5.5 kg whereas lean body mass was 49.6 ± 4.5 kg. The total arm mass was 6.6 ± 0.7 kg and the lean arm mass was 5.1 ± 0.6 kg. For the trunk, the total mass was 35.8 ± 3.4 kg and the lean mass was 30 ± 3.1 kg.

Double poling performance, as well as 1RM in the strength tests, showed the largest correlations with body, arm and trunk lean mass (Table 3). The GE_{90W} was only significantly correlated towards lean trunk mass (Table 3).

Table 3. The table shows correlations between performance and body composition in total and for different body segments for the 13 participants in this study.

	Total body mass (kg)	Lean body mass (kg)	Total arm mass (kg)	Lean arm mass (kg)	Total trunk mass (kg)	Lean trunk mass (kg)
[a]Elbow Ext. (kg)	0.62*	0.72**	0.52*	0.66*		
[b]Shoulder Ext. (kg)	0.73**	0.86**	0.66*	0.87**		
Trunk Flexion (kg)	0.48	0.70**			0.51	0.70**
[c]30-sec all-out (W)	0.78**	0.85**	0.68*	0.81**	0.65*	0.78**
[d]3-min all-out (W)	0.51	0.67*	0.30	0.55*	0.65*	0.78**
GE_{90W} (W)	0.19	0.39	-0.11	0.19	0.34	0.51*

[a] Elbow Extension; [b]Shoulder Extension; [c]30-second all-out test; [d] 3-minute all-out test.

* < 0.05 **< 0.01

Discussion

The aim of the present study was to analyze how maximal strength in the elbow, shoulder, and trunk segments, measured in isolation, influence double poling efficiency and power output among well-trained female cross-country skiers. The main findings were that the impact of maximal strength in elbow and shoulder segments increased with increasing demands of power production, whereas maximal trunk strength had a similar importance for poling efficiency and power output produced across the whole intensity spectrum. Maximal strength seemed to influence the work per cycle rather than the cycle rate. Both the power output produced in the double poling modes and the maximal strength were associated with high lean body mass in arms and trunk.

Influence of maximal strength on power output in the 30-second and 3-minute tests

The present study showed that maximal strength in upper body segments is important for the power output produced in the 30-second and 3-minute all-out tests among well-trained female skiers. Additionally, the strength variables were able to closer predict the power output in the 30-second all-out test than in the 3-minute all-out test. Other factors such as endurance capacity may explain some of the variance for the 3-minute all-out test, and may be the reason for lower correlation between the strength variables and the power output produced in the 3-minute all-out test compared to the 30-second all-out test. These findings are in accordance with previous research showing that female skiers have a great potential to improve their skiing performance by achieving higher levels of maximal upper body strength (Alsobrook & Heil, 2009; Hoff et al., 1999; Losnegard et al., 2011). In earlier studies on males was it found that the relationship between strength and power output produced was not as high as found in the present study. Additionally, males reached an upper threshold, where a further increase in strength did not provide further increase performance (Losnegard et al., 2011; Sandbakk et al., 2010; Stoggl et al., 2011). Therefore, in future studies female participants at a higher performance level should be used to investigate if the present relationships found in our study between upper body strength and power output produced in double poling are the same. Elite or world class level female skiers perhaps have a higher level of strength and less variation, which could influence the relationships. However, the group of female skiers tested in current study does not seem to have reached their upper threshold for strength and the present results show that this group of skiers could increase their power output produced in double poling by enhancing upper-body strength.

The current study also revealed that the influence of the different upper body segments differs between intensities. The elbow and shoulder segments were the strongest predictors for the power output produced in the 30-second all-out test. These findings are supported by Lindinger et al. (2009), who found an increase in activation of muscles attached to the shoulder and elbow segment at increasing work rates. The trunk segment showed similar importance for both the power output produced in the 30-second and 3-minute all out test, and was also found to be the strongest predictor of the power output in the 3-minute all-out test. These findings are supported by Holmberg et al. (2005), who showed high activation levels of muscles attached to the trunk segment at 85% of maximal race speed. A possible explanation of these findings is that the increased cycle rate in the 30-second, as compared to the 3-minute all-out test, leads to a higher use of the elbow and shoulder segment. These segments are located distally, possess a small mass and a small movement arm, and therefore effective at high cycle rates. Hence, the strength of these segments becomes more limiting for power output when these segments are used more rapidly. On the other hand, the trunk segment is a proximal segment with high mass and strength capacity, and is important in the transfer of power between legs and arms. Therefore, the trunk may have a more consistent importance for the double poling performance across the whole intensity spectrum. These possible explanations are underbuilt by Lindinger and Holmberg (2011) who found an upper threshold for cycle rate at high work rates where skiers have difficulties to effectively generate force, indicating that the cycle rate may set a limit for effective force production through different segments in the double poling technique. To increase the understanding of the segment’s role for the power output in double poling at different intensities, future research should investigate the contribution of each upper body segment during double poling and compare this to the maximal strength of each segment.

The present study also shows that maximal strength in the isolated upper body segments correlates strongly with the work performed per cycle in the 30-second all-out test. Additionally, work per cycle showed a tendency, but no significant correlation with the 3-minute all-out test. These findings indicate that the ability to create more work per cycle is influenced by strength which was expected from other studies, which have suggested that cycle length is related to strength (Bilodeau et al., 1996; Lindinger et al., 2009).

Influence of maximal strength on gross efficiency

Maximal upper body strength training has previously been shown to increase work economy (Hoff et al., 1999; Osteras et al., 2002). However, in the current study, only the trunk segment showed a significant correlation with the efficiency. These discrepancies might be explained by the fact that the studies from Hoff et al. (1999) and Osteras et al. (2002) were intervention studies and looked at effects of training, while the present study was a correlation study without any trainings effects. In our case, strength is only one of many components that may potentially influence gross efficiency between individuals. Nevertheless, a possible explanation for the correlation between maximal strength in the trunk and double poling efficiency may be that the trunk has a greater contribution in a wider range of work rates than the elbow and shoulder, and thereby becomes more important for the gross efficiency at submaximal work rates. Besides, the increase in correlation from the 3-minute to 30-second all-out test for elbow and shoulder strength could indicate that the shoulder and elbow depend on work rate. Therefore, it is reasonable to assume that the work rate on the GE_{90W} was not high enough for the elbow and shoulder strength to have an influence on the gross efficiency. However, none of the strength variables in the multiple regression analyses were able to significantly predict gross efficiency, indicating that strength does not play a crucial role for the gross efficiency in this locomotion, whereas other factors such as technique and muscular endurance may be of higher importance.

Influence of body composition on maximal strength and power output in double poling

Both power output produced in the SkiErg and maximal strength were strongly related to lean body mass in the arms and trunk. These findings are in accordance with previous research on males, showing that lean body mass in the arms and trunk is an important factor for the performance in double poling (Larsson & Henriksson-Larsen, 2008; Stoggl, Enqvist, Muller, & Holmberg, 2010). Since both poling performance and maximal strength were associated with high lean body mass in arms and trunk, there are reasons to believe that enhanced upper body muscle mass may be advantageous for double poling performance among female skiers, especially when considering that one of the biggest gender differences can be found in the amount of the upper body muscle mass (Zatsiorsky & Kraemer, 2006)

Methodological considerations

Although FIS points as an indication of skiing performance level strongly correlated with power output in the 3-minute all-out test and gross efficiency, which indicate that these double poling tests are of high relevance to the skiing performance level, power output produced in the ergometer is not the same as the performance level on snow. Power output produced in the ergometer not is influence by air drag or snow friction, which interferes with the double poling performance on snow. Since air drag will increase with higher skier areal and snow-ski friction will increase with increasing body mass, it is reasonable to suggest that a person with high body mass (including muscles which may positively influence strength) that produces a high power output has some disadvantages on snow that is not present with ergometer poling.

Furthermore, Linnamo et al. (2013), have shown that ergometer poling differ from snow, with longer poling times across intensities. However, quite similar muscle activities and fatigue loading between the ergometer and skiing where found. This, suggest, that the ergometer leads to quite similar results from investigations of cycle characteristics, force production and muscle activities as it would be for snow.

Practical applications

Based on the high correlation between upper body maximal strength and power output produced in double poling, and considering that females in general terms are weaker than males, female skiers may benefit by putting more emphasis on strength training. This might be especially important since females have 10 to 20 times less testosterone than males (Zatsiorsky & Kraemer, 2006), and thereby are less responsive to muscle adaptations in the upper-body from both, strength and general cross-country skiing training. The current study also shows that the maximal dynamic strength in the trunk segment may be of importance for the double poling performance. This indicates that the strength sessions preformed for this segment should implement maximal dynamic training and not only stabilization training.

Conclusions

The current study demonstrates that the impact of maximal strength in elbow and shoulder segments for power output produced in double poling increased with increasing demands of power production, whereas maximal trunk strength was equally important for poling efficiency and power-output across the whole intensity spectrum. Additionally, the strength variables were able to closer predict the power output in the 30-second all-out test than in the 3-minute all-out test. The study, therefore, indicates that female skiers are a group of athletes with great potential to improve their power output produced in double poling by enhancing maximal upper body strength, and that the importance of maximal strength increases with increased intensity. Maximal upper-body strength mainly seems to influence work per cycle and not cycle rate. Since both power output in double poling and maximal strength were associated with high lean body mass in arms and trunk, enhanced upper-body muscle mass may be advantageous for female skiers.

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