EFFECT OF SKI POLE STIFFNESS ON UPPER BODY POWER OUTPUT IN
CROSS-COUNTRY SKIERS

by

Erik Andrew Jacobson

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Approved for the Department of Health and Human Development

Tim Dunnagan, EdD

Approved for the Division of Graduate Education

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ABSTRACT

The purpose of this study was to determine whether increased pole stiffness corresponds with higher measures of upper body power in competitive cross-country skiers. Fifteen elite/college level cross-country ski racers (8 men, 7 women) tested UBP on a custom-built double-poling ergometer. Ski poles tested were two models of the same brand with different factory-specified stiffness ratings. Subjects underwent three 10 s UBP tests (W_{10} , W) and one 60 s UBP test (W_{60} , W) for each pole type. UBP measures were defined as the average power output over the length of each test. Video recordings of the 10 s and 60 s tests were analyzed with digital imaging software to determine the maximum bend angle for each pole type. Ergometer and kinematic measures were compared by ski poles tested (stiff vs. less stiff) using a multivariate RMANOVA ($\alpha=0.05$). Measures of W_{10} and W_{60} for stiff and less stiff poles did not differ significantly ($P=0.077$, 0.077). However, a post-hoc evaluation determined that men had higher W_{60} values with the stiff poles ($p = 0.014$). Maximum poling angles were greater when using less stiff poles for both the 10 s ($p = 0.003$) and 60 s ($p < 0.001$) tests. However, a post-hoc evaluation discovered that when grouped by gender, only male subjects created greater bending with the less stiff poles ($p = 0.003$, $P < 0.001$ for 10 and 60 s tests, respectively). For both 10 and 60 s tests, Pearson's product moment correlation coefficients were calculated between differences in pole bend ($\Delta\text{flex}_{10, 60}$) and differences in power output ($\Delta W_{10, 60}$) as well as absolute power output ($W_{10, 60}$). Δflex correlated well with ΔW for both tests ($r = 0.62$, 0.59 for 10 s and 60 s tests). W_{10} and W_{60} were the best predictors of pole bend in their respective tests ($r = 0.86$, 0.94 for 10 and 60 s tests). These findings suggest that only skiers with highest power output will be able create enough pole bending to affect measures of UBP between poles with slight differences in stiffness.

CHAPTER ONE

INTRODUCTION

Cross-country skiing is a method of overland travel on snow-covered terrain. The sport of cross-country skiing has been a competitive event at the Winter Olympics since its inception in 1924. The original, or “classic”, style resembles a running gait where the athlete strides by shifting between skis. Each stride is composed of pushing off one ski and gliding on the other. In this style, the skis are kept in parallel prepared grooves in the snow, or “classic tracks”. Grip wax is applied to the ski bases to enable the athlete to push against the snow. During the push-off, or “kick phase”, each arm alternately poles with the opposite side leg to aid propulsion. This classic technique is specifically known as the striding or single-stick technique and is mostly used when climbing moderate to steep hills. Other classic techniques are the double-pole and the kick-double-pole. On even terrain, the double-pole technique is most often used. This technique entails keeping the legs side by side with no striding, while the arms pole in unison. The kick-double-pole is used in flat terrain and lower grade climbs. The kick-double-pole differs from the double-pole by incorporating a single leg kick phase immediately prior to the pole plant. In addition to these classic skiing techniques, a new “freestyle” skiing method appeared in professional competitions in the early 1980’s. This new style used the classic double-pole motion of the arms while the athlete’s legs pushed off and glided from side-to-side in a skating motion. Like classic style skiing, there are a variety of freestyle techniques. The V2 technique, employed in flat to rolling terrain, is used most often and utilizes

double-poling with each skating step. The V2-alternate technique, in contrast, consists of poling on only one side at a time and is used when high speeds or energy conservation make poling with each stride unnecessary. In the V2 techniques, the pole plant occurs immediately prior to shifting one's weight to the gliding ski. Lastly, the V1 technique is used for climbing and resembles V2 alternate in that poling occurs on only one side at a time. However, with V1, the pole plant coincides with the shift to the gliding ski (as opposed to just prior to the shift in V2). Combining the weight shift with the pole plant and increasing cadence gives the athlete the ability to climb steep hills efficiently with the V1 technique. Currently, races are designated beforehand as either classic or freestyle, and the athletes must adhere to the specified style.

Researchers have shown that upper body power (UBP) is one of the most essential predictors of cross-country ski performance (Gaskill, Serfass, & Rundell, 1999; Hoff, Helgerud, & Winslof, 1998; Mahood, Kenefick, Kertzer, & Quinn, 2001). Upper body power in cross-country skiing is defined as the amount of power produced by the arm, shoulder, back, and trunk muscles during the poling motion. In cross-country skiing, UBП is most important when a racer attempts to break from a pack or climb steep grades, as well as during sprint finishes. Therefore, increased UBП could give athletes an advantage in contemporary races, which are often decided by less than one second. Higher UBП may also be linked to improved double-pole economy (Hoff et al., 2002).

While not all cross-country ski techniques emphasize use of the legs, the upper body is employed in every classic and skating motion. For example, poling provided about 66% of the propulsive force in a study of V1 kinematics (Street, 1989). Techniques

such as the V2 in skating style and the double pole or kick-double-pole in classic style likely rely even more on the upper body for propulsion. It is therefore appropriate to measure power output in cross-country skiers with a test that isolates force production of the upper body. Furthermore, the energy supplied by the upper body is transferred to the snow solely through ski poles. Thus, the amount of UBP an athlete can transfer to the ski track may be affected by a ski pole's ability to transmit force from the upper body to the snow.

Considering the importance of UBP, the effectiveness of the poles in transferring force to the snow could be a contributing factor to race performance. It is possible that stiffer ski poles could positively affect the transfer of UBP to the ski track. Ski poles vary in stiffness and weight depending on their composition. Decreased stiffness causes a pole to bend more under poling forces. A true test of stiffness requires stressing a material until it breaks. Therefore, pole bending angles will be used in this study to verify the differences between factory-specified stiffness ratings (CT1 is 25% stiffer than CT3, Swix Sport, 2008). Currently, ski poles are manufactured from aluminum, fiberglass, carbon-fiber, and, most commonly, a mix of fiberglass and carbon-fiber. Generally, aluminum poles have the most deflection under poling forces (i.e. least stiff), followed by fiberglass. Conversely, carbon-fiber has 2.5 times the stiffness of fiberglass and is 25% lighter (Street, 1992). Since higher carbon-fiber content increases a pole's stiffness and decreases its weight, it is the material of choice for construction of the finest quality poles.

Recent advances in pole manufacturing have resulted in stiffer poles than any previous design. It is unclear whether a high-quality carbon-fiber pole can cause a significant increase in power transfer (i.e., influence measures of UBP) when compared to a mid-grade pole.

Statement of the Purpose of the Study

The purpose of this study is to determine whether ski pole stiffness has a significant impact on measures of UBP in cross-country ski racers during the double-pole motion.

Hypotheses

Primary Hypothesis

Measures of UBP will be higher during tests using stiff pole shafts (s), when compared to less stiff shafts (l).

$$H_0: \mu_s = \mu_l$$

$$H_a: \mu_s < \mu_l$$

where μ_s is the population average for UBP using stiff poles and μ_l is the population average for UBP using less stiff poles.

Secondary Hypothesis

Stiff pole shafts (s) will bend less than less stiff shafts (l) during tests of UBP.

$$H_0: \mu_s = \mu_l$$

$$H_a: \mu_s < \mu_l$$

where μ_s is the population average for pole bend using stiff poles and μ_l is the population average for pole bend using less stiff poles.

Limitations

Ski poles used in this study ranged in length from 135 cm to 160 cm in 5cm increments. Some subjects may have had to use slightly longer or shorter poles than they were accustomed to when skiing.

Assumptions

It was assumed that UBP values from the ergometer were representative of each athlete's power output during on-snow double poling.

Delimitations

Only technically skilled skiers with experience in national-level competitions were used in this study.

Operational Definitions

Classic Style:	The original style of skiing in which the athlete strides by shifting between skis. Poles are used such that each arm pushes off in conjunction with the opposite side ski. Skis run parallel to each other in prepared tracks.
Double Pole:	A classic style technique in which the legs are kept stationary while both arms simultaneously push the ski poles. Generally used in flat or gently rolling terrain, this upper body motion is also used in conjunction with the propulsive forces from the legs in the skating style.
Skating Style:	A newer compilation of skiing techniques that involve positioning the skis in V-shaped formation and shifting between skis in a skating motion. Arms are used in double pole motion on each stride or every other stride, depending on the specific technique being used.
Upper Body Power (UBP):	Rate of work performed during cross-country skiing using the arm, shoulder and trunk muscles.
Maximal Oxygen Uptake (VO_{2MAX}):	The maximal rate of oxygen consumption that a subject is capable of during exercise. In the case of this study, the exercise is ski-bounding on a treadmill. Ski-bounding incorporates the use of poles with a bounding gait that mimics the striding technique in classic style skiing.
Respiratory Exchange Ratio (RER):	The ratio of the rate of carbon dioxide exhaled to the rate of oxygen consumed (VCO_2/VO_2).
W_{10} :	Average power output (W) during the 10 s maximal ergometer test.

W_{60} :	Average power output (W) during the 60 s maximal ergometer test.
Maximum bending angle	Average of the greatest pole bend (degrees) value from five successive poling cycles.
ΔW	Difference in power output (W) between stiff and less stiff poles for the 10 s (ΔW_{10}) or 60 s (ΔW_{60}) test.
Δflex	Difference between maximum bending angles (degrees) between stiff and less stiff poles for the 10 s (Δflex_{10}) and 60 s (Δflex_{60}) test.

CHAPTER 2

REVIEW OF THE LITERATURE

Introduction

Technological advances in cross-country ski equipment, including the introduction of composite materials such as carbon-fiber, have greatly changed the nature of equipment being used and the speed of ski races. For example, contemporary ski poles are lighter and much stiffer than their predecessors, due to the use of 100% carbon-fiber shafts and incorporation of increasingly higher modulus carbon. Specifically, upper body power is an important variable of ski performance that could be affected by recent technological advancements in ski pole manufacturing.

Determinants of Performance

Maximal oxygen consumption (VO_{2MAX}) is a known predictor of performance in heterogeneous populations (Evans, Davy, Stevenson, & Douglas, 1995; Costill, Thomason, & Roberts, 1973). Energy expenditure is commonly measured by the rate of oxygen consumption (VO_2) while VO_{2MAX} defines an individual's upper limit for VO_2 . However, among populations with similar endurance performances, VO_{2MAX} seldom has a high correlation to performance (Hagberg & Coyle, 1983; Impellizzeri, Marcora, Rampinini, Mognoni, & Sassi, 2005; Larsson, Olofsson, Jakobsson, Burlin, & Henriksson-Lasen, 2002; Morgan, Baldini, Martin, & Kohrt, 1989) and the importance of VO_{2MAX} in running performance has been shown to vary significantly in runners trained

for distances of 800 m versus 1500 and 3000 m (Brandon & Boileau, 1992). Thus, $\text{VO}_{2\text{MAX}}$ may not be the most important predictor of performance in cross country skiers, who must compete at distances between 1 and 50 km. Furthermore, Powers, Dodd, Deason, Byrd, and McKnight (1983) showed that VO_2 at ventilatory threshold (VT, the point at which expired ventilation increases rapidly during graded exercise; Powers et al., 1983) correlated with running performance ($r = 0.94$) far better than $\text{VO}_{2\text{MAX}}$ ($r = 0.38$) in trained athletes. Similarly, Larsson et al. (2002) found VO_2 at lactate threshold (LT, the point at which blood lactate concentration increases rapidly during graded exercise; Basset & Howley, 2000) to correlate with performance ($r = 0.95$) better than $\text{VO}_{2\text{MAX}}$ ($r = 0.80$) in trained cross-country skiers. Although LT is not the same physiological measure as VT, the two measures often occur at similar rates of oxygen consumption (Powers et al., 1983). It is likely that the measure of VO_2 at LT (or VT) correlates well with performance due to its very close relationship to the percent of $\text{VO}_{2\text{MAX}}$ used by athletes during endurance competitions (Basset & Howley, 2000).

Thus far, discussion has been focused on physiological factors that affect performance, but populations exist with similar values for $\text{VO}_{2\text{MAX}}$ and LT. In cases of homologous populations, variances can still be seen in performance (Morgan et al., 1989), and males perform at a higher level than females with similar $\text{VO}_{2\text{MAX}}$ values (Daniels & Daniels, 1992). Specifically, differences in these populations can be determined when speed at $\text{VO}_{2\text{MAX}}$ is taken into account. Furthermore, variance in speed is likely due to differences in individual economy (oxygen consumption required while

performing a specific amount of work; Cavanagh & Kram, 1985) and accounts for differences in performance not due to $\text{VO}_{2\text{MAX}}$ or LT.

Measuring speed at LT is regarded as a more accurate variable for predicting endurance performance (Basset & Howley, 1997; Imellizzeri et al., 2005; Hagberg & Coyle, 1983) because it combines the factors of $\text{VO}_{2\text{MAX}}$, VO_2 at LT and economy in a summarized performance model by Basset & Howley (1997). This was evidenced by Hagberg & Coyle (1983) in a heterogeneous group of racewalkers, which had a higher correlation of race speed with speed at LT ($r = 0.94$) than to measures of $\text{VO}_{2\text{MAX}}$, VO_2 at LT and economy ($r = 0.62, 0.82$, and 0.89 respectively). Any predictive measure can be difficult to correlate with performance, however, when dealing with very homogenous populations (Basset & Howley, 1999). Impellizzeri et al. (2005) showed that power output at a specific level of energy expenditure (similar to race intensity, $87.5\% \text{VO}_{2\text{MAX}}$) was a better predictor of performance than $\text{VO}_{2\text{MAX}}$ or VT in high level cross-country off-road cyclists. Further, this result fits the model of endurance performance since power output also takes into account the VO_2 at LT and economy.

In Basset & Howley's performance model the final variable of power at LT is divided by the external power demand. In order to determine performance in cross-country skiing, an athlete's power output must overcome the factors of gravity, drag (ski on snow), and aerodynamic drag (Frederick, 1992). Assuming the external power demand factor is the same for all competitors, power output during race intensity (near LT or VT) could closely determine performance. However, peak power output, as opposed to power output at LT, may be used to accurately predict performance in trained cyclists (Coyle,

Feltner, Kautz, Hamilton, Montain, Baylor, Abraham, & Petrek, 1991; Hawley & Noakes, 1992; Heil, Murphey, Mattingly, & Higginson, 2001) and cross-country skiers (Alsobrook, 2005; Gaskill et al., 1999; Heil et al., 2004; Mahood et al., 2001). The rolling terrain in ski courses causes periods of near complete recovery on downhills and explosive effort on uphills, which may explain the high correlation of peak power outputs with performance in cross-country skiers.

Upper Body Power

In the sport of cross country skiing, research has shown that upper body power may be a better predictor of performance than more traditional standards such as VO_{2MAX} and LT (Gaskill et al., 1999; Mahood et al., 2001; Rundell & Bacharach, 1995; Staib, Im, Caldwell, & Rundell, 2000). Upper body power (UBP) in cross-country skiing is the rate of work being performed by the arm, shoulder, and trunk muscles when pushing on the ski poles.

Mahood et al. (2001) showed that a 1 km uphill double pole time trial had the highest correlation with race performance in collegiate level ski racers when compared to more conventional measures such as VO_{2MAX} and LT. The time trial, being a test that was brief and high intensity in nature and isolated the upper body for propulsive force, was used as a measure of UBP. This test was correlated highly with the results of a 10 km freestyle time trial ($r = 0.95$) and the overall season rank of the skiers ($r = 0.92$). Rundell & Bacharach (1995) also used a battery of tests to predict racing ability in skiers. The researchers proposed that due to the major involvement of the upper body in cross-

country technique, UBP would be an important determinant of performance. The authors plotted test results against the subjects' (male and female elite level biathletes) national rankings. As expected, VO_{2MAX} and LT were found to correlate well with rank. However, the most significant correlations with season rank were found to be peak UBP output (measured as power output during a 10 s double pole power test) and a 1 km uphill double-pole time trial. The women in the study had a high correlation between power outputs on the 10 s double-pole ergometer test and season rank ($r = 0.95$), while no significant correlation was found for men. However, 8 men participated in a 1 km uphill double-pole time trial which was found to correlate highly with season rank ($r = -0.83$).

The studies of Mahood et al. (2001) and Rundell & Bacharach (1995) showed upper body power to be an important predictor of performance in elite and college level athletes. Gaskill et al. (1999), however, used 124 high school skiers and 34 adult skiers of mixed ability to test the influence of upper body power on athletes with less skill. Measures of UBP were determined by an incremental test on a double-pole ergometer. Each stage lasted 20 s with the subject maintaining a minimum flywheel RPM. Resistance was increased for each stage until the subject could no longer maintain the minimum RPM. The researchers plotted the values against the athletes' race speed. Race speed was calculated using the average (distance (m) /time (s)) of a competitor's 2-4 best races. The authors discovered that UBP had a strong correlation with race speed in all ages and abilities ($r = 0.83$). Furthermore, it is important that skiers have high power outputs relative to their weight because UBP/kg had an even stronger correlation with race speed ($r = 0.89$).

Interest in the importance of UBP led researchers to test if increases in power production could affect performance. Hoff et al. (1998) predicted that short, high intensity weight training with heavy loads would produce the most improvement in UBP. Regional level skiers completed a nine week training regimen that consisted of one double-pole mimicking exercise; done at the maximum resistance a subject was able to successfully complete the exercise for 3 sets of 6 repetitions. Also, a control group was included in which subjects spent a similar amount of time (compared to the experimental group) using general low intensity strength training. After the training cycle, the two groups underwent 1 repetition max and peak force testing using the double-pole specific exercise and a graded (with resistance) test to exhaustion (TTE) on a double-pole ergometer. Subjects who were conditioned using the high intensity training program showed a significant increase in peak force and exhibited a 79% greater improvement compared to the control group in a double pole ergometer TTE test. A follow-up to the Hoff et al. (1998) study showed similar increases and attributed the performance improvement to neurological adaptations in the skeletal muscle, since no changes in $\text{VO}_{2\text{MAX}}$ or muscle mass were detected (Osteras, Helgerud, & Hoff, 2002). These muscular adaptations ultimately benefited performance by allowing the subjects to complete the TTE test at a lower percentage of their peak force, thereby improving double-pole economy. Once again, power output was shown to be a good predictor of performance due to its ability to take into account economy, $\text{VO}_{2\text{MAX}}$, and LT. This is especially important when dealing with homologous populations, such as elite endurance

athletes, who are likely to have very similar physiological characteristics, making it difficult to correlate any one value with performance.

Many researchers have shown that upper body power is important to ski performance, but there is no standard measurement of upper body power in skiers. In an attempt to determine the most viable upper body test for predicting ski performance, Alsobrook (2005) used 10 s and 60 s maximal tests as well as peak power recorded during an incremental TTE on a double-pole ergometer. The subjects took part in a 10 km classic style race to determine race speed (m/s) for a measure of performance. Not only did all measures of upper body power correlate highly with race speed ($r = 0.93$ for 10 s, $r = 0.92$ for 60 s, and $r = 0.94$ for peak power), but these values also correlated highly with each other. Therefore, the anaerobic tests of 10 s and 60 s appear to be a more useful test protocol due to their equal viability as compared to the more time-consuming aerobic test.

Equipment Influences

Adjustments in technique have been observed in elite level skiers in the last ten years. Racers now stand more upright in order to put as much downward force as possible on the ski poles and rely more heavily on the upper body dependant techniques of the V2 in freestyle and the double pole in classic style skiing (Millet, Martin, Hoffman, Candau, & Clifford 1998a). These adjustments are likely due to the increased stiffness of ski poles and more intense upper body training regimens (Hoff et al., 2002; Osteras et al., 2004; Nilsson, Holmberg, Tveit, & Hallen, 2004) designed to allow athletes to take full

advantage of the poles' ability to withstand higher downward forces. Furthermore, with the advent of the sprint format (races 1- 1.5 km in length), athletes are specializing in skiing at much higher speeds which can increase poling forces by 20-40% for every 3 km/hr increase in ski speed (Smith, 1989). Poles also undergo 50-60% greater poling forces over a 3% rise in grade (Millet, Martin, Hoffman, Candau, & Clifford, 1998b). Thus, it is possible that stiffer poles have allowed skiers to travel up steep grades more effectively.

After physiological measures, the next most influential factor in ski performance is equipment (Street, 1992). Few researchers have tried to determine if differences in equipment could influence power output in cross-country skiers. When performing a task on an ergometer, some amount of energy is used deforming the apparatus (ski poles, in the case of the present study) and goes unmeasured (Cavanagh & Kram, 1984). Therefore, measuring the power output of subjects using different ski poles will determine the energy lost to the ergometer due to the change in equipment. The first study of this kind by Hartner, Hilden, & Street (1991) evaluated the effects of four types of ski pole grips on economy in skiers. Although no significant differences were discovered, Street (1992) suggested that subtle differences in grip design could still play an important role in high intensity efforts, such as hill climbing or finishing, and should be evaluated using maximal force tests. The most recent experiment of this kind, by Heil, Engen, & Higginson (2004), attempted to determine the influence of three different ski pole grip designs on maximal UBP. Eleven experienced skiers (9 men, 2 women) participated in 10 s maximal UBP testing similar to Alsobrook et al. (2005). The subjects

underwent UBP testing for each of three types of ski pole grip; a traditional single loop strap grip and two modern grips with more substantial straps for the hand/pole grip interface. The researchers found that athletes using one of the modern pole grip designs, which differed from the others by having an integrated thumb rest on the interior aspect of the pole grip itself, transferred more power than the other two designs (169.2 watts vs. 164.1 and 162.5 watts for Integrated, Modern, and Traditional mean UBP, respectively). Therefore, researchers concluded that equipment could possibly affect race performance. The two previous studies are the only known attempts to determine the ski pole's influence on performance. A 1992 article by Street predicted that the 42 g difference between the heaviest and lightest race poles at the time could save a skier 1-3 s over a distance of 30 km. However, recent improvements have focused on swing weight (reducing weight at the pole tip to increase speed of the pole swing motion) and shaft stiffness (longitudinal stiffness of the ski pole) over weight savings. Although Street suggests that stiff poles will transmit forces more effectively, no research has yet determined the effect of pole stiffness specifically on ski performance.

Summary

Maximal oxygen uptake (VO_{2MAX}) and LT are good predictors of cross-country ski performance (Larsson et al., 2002; Mahood et al., 2001; Rundell & Bacharach, 1995). However, it has been shown that short duration tests of upper body strength are superior determinants of a skier's ability (Mahood et al., 2001; Rundell & Bacharach, 1995). Researchers (e.g. Hoff et al., 1998; Osteras et al., 2004) have also discovered that

maximal strength weight training can improve the results of such trials by increasing UBP and economy. The training was most effective at increasing power when targeting neural adaptations such as rate of movement (Hoff et al., 2002; Nilsson et al., 2004; Osteras et al., 2004). It has also been shown that equipment may influence UBP output in short duration maximal trials (Heil et al., 2004). In conclusion, UBP and has been shown to be very important physiological component of success in cross-country ski racing (Hoff et al., 1998; Nilsson et al., 2004; Mahood et al., 2001; Osteras et al., 2002; Rundell & Bacharach, 1995) and it is unclear to what extent pole stiffness affects UBP.

CHAPTER 3

METHODOLOGY

Subjects

Fifteen cross-country skiers (8 men, 7 women) from Bozeman, Montana volunteered to participate in this study. All subjects were between the ages of 18 and 30 and were currently competing in the sport of cross-country skiing. Subjects read and signed a Montana State University IRB committee-approved informed consent document explaining the requirements and potential risks of participation in the study.

Procedures

The testing period was comprised of three visits, all of which were no more than six weeks apart, including the second and third visits being within a two week period. The first visit consisted of gathering relevant descriptive information (height, age, weight) and an incremental test to exhaustion (VO_{2MAX} test) on a treadmill with subjects ski bounding with ski poles. The test was followed by a five minute submaximal workout on the double-pole ergometer in order to familiarize subjects with the machine and the testing protocols. The second and third visits were for testing UBP with the two types of ski poles on the ergometer. Half of the subjects tested with the stiff poles on the first visit and the less stiff poles on the second visit, with the remaining subjects testing the poles in the opposite order. The testing session consisted of a warm-up followed by three 10 s maximal tests and a 60 s maximal test.

VO₂MAX Testing Protocol

The session began with recording height, weight, age and sex of each subject and concluded with an incremental test to exhaustion in order to determine VO_{2max} and maximum heart rate (HR_{max}). Maximal oxygen consumption (VO_{2max}) is a widely accepted determinant of endurance performance and is important for defining the fitness of the population studied. The test was performed on an oversized treadmill with variable speed and grade. The individuals used ski poles with a walking or bounding (depending on treadmill speed) stride emulating the arm and leg swings of classic skiing. This “ski bounding” motion is a typical off-season training technique with which all subjects were well practiced. Subjects breathed through an apparatus which allowed room air in for inspiration and collected expired air for sampling the rate of oxygen consumption. Before the data collection began, subjects were fitted with a heart rate monitor and allowed to warm up on the treadmill. The purpose of the warm up was to prepare the body for exercise and to familiarize the subjects with the test protocol and the treadmill’s starting and stopping safety procedures. The initial stages of the test consisted of three minutes at a fixed speed and grade of 6% and 3.7 mph, followed by one minute of fingertip blood lactate sampling with the treadmill stopped. The treadmill was re-started so that the subject could start the next stage, and speed and grade were increased by 2% and 0.3 mph. During each stage, the lactate concentration was analyzed by a technician using a handheld sampling device. After a minimum 2 mmol spike in lactate (i.e., subjects had exceeded lactate threshold) stages were shortened to one minute, with no stops or blood sampling, and continued until volitional exhaustion. To verify that the test was maximal,

subjects' test data had to satisfy two out of the following three criteria for achieving $\text{VO}_{2\text{max}}$: 1) maximal respiratory exchange ratio (RER) of 1.1 or greater, 2) an increase in workload without an increase in oxygen consumption (VO_2 plateau), and 3) a heart rate (HR) within 10 beats of age-predicted maximal heart rate ($220 - \text{age in yrs}$). Following the $\text{VO}_{2\text{max}}$ test, subjects were allowed to warm down on the treadmill before completing a short familiarization training session on the double pole ergometer.

Upper Body Power Testing

Upper body power tests were performed on a double pole ergometer which was outfitted with ski poles similar in length to each subject's own classic style ski poles (see Figure 3.1). Some subjects had to use poles slightly longer or shorter than preferred because poles were only available in 5 cm increments. The athletes performed three consecutive trials of a 10 s power test and a 60 s power test with a two min rest period between each trial. The validity of performing 10 s and 60 s UBP tests on the ergometer was established with previous research, which showed both measures to correlate highly with ski performance and with each other (Alsobrook et al., 2005). The 10 s power test lasted a total of 30 seconds and started with a 20 second build up, during which the subjects were instructed to gradually increase the double-poling effort. Between the 20th and 30th s of the test, subjects gave a maximal double-poling effort. The power output for the 10 s upper body test (W_{10} , W) was determined by calculating an average power over the final 10 s and then selecting the highest average from the three trials. The 60 s power output (W_{60} , W) was determined by averaging power values from a single 60 s test, where the individual started from a dead stop.

Kinematic Analysis

Two dimensional sagittal-view video recording of the ergometer tests was used to measure pole bending during the UBP tests. Three reflective markers were placed on the poles, with the first marker placed 4 cm below the bottom of the grip, the second marker placed at the distal end of the pole shaft, just above the tip, and the third marker at the midpoint of the other two. During a poling cycle, a ski pole bends in the sagittal plane as a result of downward poling forces. The bend of the pole was measured by calculating the angle (degrees) between the two outside points when the center marker moved out of line from the other two. Thus, an increased bending angle was proportional to increased bending of the pole shaft. The maximum bending angles during the 10 s and 60 s UBP test were calculated as an average of the highest bend angle from five successive poling cycles. The period of five poling cycles took four to five seconds for each subject and was sampled from the middle of each test.

Instrumentation

Double-pole Ergometer

All testing was performed on a modified Concept 2 Model D rowing ergometer (Concept 2, Morrisville, VT, USA). The ergometer included of a large air-resisted flywheel connected to an 8-foot long square beam. Subjects stood on a platform at the point where the beam connected to the flywheel. A resistance-loaded trolley ran along the beam and was connected to the flywheel with static cord. In order to measure power output, the athletes pushed the trolley down the beam with the attached ski poles. The

poles were interchangeable and were switched to fit each skier's preferred length. Pole lengths were available in 5 cm intervals, but the same pole length was used for each pole type tested.

Figure 3.1. Photo of a subject testing on the double-pole ergometer.

Video Analysis

10 s and 60 s tests were recorded with a 60 Hz Digital Color Video Camera (JVC TK C1380, JVC Americas Corp., Eayne, NJ, USA) at a distance of four meters from the ergometer. The video was analyzed with Peak Motus Version 7.1 Kinematic Analysis Software (Peak Performance Technologies, Inc. Englewood, CO, USA). A fast Fourier

transformation (FFT) with a window size of three was used to decrease signal noise while still maintaining the integrity of the signal peaks (maximum bending angles).

VO_{2max} Testing

Oxygen uptake during the test to exhaustion was measured by a TrueMax 2400 Analyzer Module (Parvo Medics, Sandy, UT, USA). Oxygen consumption values were summarized over 20 s samples. Prior to testing, the metabolic system was calibrated for gas concentration with a gas mixture of 16.02% O₂ and 4.0% CO₂ (balanced with N₂) and was calibrated for volume measurement with a 3-Liter calibration syringe (Series 5530, Hans Rudolph, Inc., Kansas City, MO, USA). The oversized treadmill used for ski bounding was a JAS Trackmaster (Full Vision, Newton, KS, USA). Heart rate was measured using a Polar Vantage Heart Rate Monitor with Wear Link strap (Polar Electro Inc., Lake Success, NY, USA). Heart rate was sampled every 20 s.

Ski Poles

Poles described as “stiff” were made with Swix Star CT1 100% UHM/HM carbon fiber shafts with a stiffness rating of 30 mm (factory specified stiffness ratings) and a weight of 59 g/m. Poles described as “less stiff” were made with Swix Carbon CT3 80% HS carbon fiber/20% fiberglass shafts with a stiffness rating of 40 mm and a weight of 78 g/m (Swix Sport AS, Lillehammer, Norway). All poles were outfitted with Swix PCC handles and Pro Fit straps (Swix Sport AS, Lillehammer, Norway).

Statistical Analysis

The dependent variables for this study included values of W_{10} and W_{60} (W) from the 10 s and 60 s trials, as well as maximum pole bending angle (degrees) from the 10 s and 60 s trials, respectively. In addition, the difference in UBP (ΔW , W) and the difference between maximum bending angle between pole types ($\Delta flex$, degrees) for both 10 s and 60 s trials were computed for post-hoc correlational calculations. Differences in UBP and bending angles between the two pole types were determined with multivariate one-factor repeated measures ANOVA using Statistica Version 7 (StatSoft, Tulsa, OK, USA). Significant differences between groups were determined using an alpha level of 0.05. The Pearson's Product moment correlation was used to determine relationships between $\Delta flex$ and ΔW for 10 s and 60 s as well as relationships between $\Delta flex$ and UBP for 10 s and 60 s tests. Alpha level was set at 0.05.

CHAPTER 4

RESULTS

The purpose of this study was to determine the effect of ski pole stiffness on measures of upper body power (UBP). Two maximal tests of UBP lasting 10 s (W_{10}) and 60 s (W_{60}) were completed on a double-poling ski ergometer. Two types of ski poles, differing only in stiffness, were tested by each subject on different days; no more than a week apart. One subject was retested due major differences in technique between testing sessions.

Subjects were 15 (eight male, seven female) well-trained cross-country skiers. All subjects completed tests for both pole types as well as a graded test to exhaustion while ski-bounding on a treadmill. Values for VO_{2MAX} were recorded after determining that each subject met the criteria for achieving maximal oxygen consumption. Age, height, weight, and VO_{2MAX} (relative to body mass) are shown in Table 4.1. Mean values for all UBP tests are summarized in Table 4.2

Table 4.1. Descriptive statistics for subjects (Mean $\pm$ SD).

Gender	n	Age (yrs)	Body height (cm)	Body mass (kg)	VO_{2MAX} (ml/kg/min)
Male	8	22 $\pm$ 3	186.0 $\pm$ 4.9	78.3 $\pm$ 5.9	64.9 $\pm$ 4.7
Female	7	21 $\pm$ 3	169.7 $\pm$ 5.1	61.8 $\pm$ 4.4	53.4 $\pm$ 5.0

VO_{2MAX} = maximal oxygen consumption.

Table 4.2. Summary statistics for UBP measures with stiff and less stiff poles (Mean $\pm$ SE).

Gender	Stiff poles		Less stiff poles	
	W_{10} (W)	W_{60} (W)	W_{10} (W)	W_{60} (W)
All	255 $\pm$ 32	208 $\pm$ 24	248 $\pm$ 32	201 $\pm$ 22
Male	358 $\pm$ 21	286 $\pm$ 14*	346 $\pm$ 22	273 $\pm$ 14*
Female	137 $\pm$ 9	118 $\pm$ 7	136 $\pm$ 6	129 $\pm$ 17

* Denotes significant difference between UBP measures with stiff and less stiff poles ($P < 0.05$).

W_{10} = Power output from 10 s test; W_{60} = Power output from 60 s test.

Although not significant, there was a tendency for subjects to have higher values of UBP for W_{10} ($p = 0.077$) and W_{60} ($p = 0.077$) when using the stiff poles. After grouping by gender, there were no significant differences due to pole stiffness for women for either W_{10} or W_{60} . However, there was a significant increase (273 to 286 W) in W_{60} power for men using the stiff poles ($p = 0.014$). There was also a tendency for men to have higher W_{10} power output with the stiff poles (346 to 358 W; $p = 0.066$).

Video analysis of subjects' 10 s trials was used to determine the maximum bending angle for each pole type. Mean values for stiff and less stiff pole bending angles are summarized in Table 4.3.

Table 4.3. Summary statistics for degrees of pole bending during 10 s UBP tests (Mean $\pm$ SE).

Gender	Maximum bending angle for stiff poles (degrees)	Maximum bending angle for less stiff poles (degrees)
All	2.2 $\pm$ 0.3*	4.1 $\pm$ 0.7*
Male	3.0 $\pm$ 0.2*	6.3 $\pm$ 0.7*
Female	1.2 $\pm$ 0.1	1.6 $\pm$ 0.2

* Denotes significant difference between stiff and less stiff pole bending angles
 Maximum bending angle = average of the maximum pole bending angle, in degrees, from five successive poling cycles.
 Degrees = degrees past 180.

Less stiff poles bent significantly more than stiff poles ($p = 0.003$). Although there was a tendency for women to have greater bending angles with the less stiff poles ($p = 0.052$), only the male subjects exhibited a significant difference between pole types ($p = 0.003$). Figure 4.1 graphically demonstrates the change in bending angle for stiff and less stiff poles over a period of five poling cycles during the 10 s test of subject 1 (female) while Figure 4.2 is the graph for male subject 14. To facilitate direct comparisons between graphs, both figures are displayed with the same x and y scales.

Figure 4.1 Pole bending angle of stiff (red) and less stiff (black) poles over a period of five poling cycles during the 10 s test of subject 1 (female). The 180° line represents a pole in its linear state (no bend). Positive bending angles are representative of poles bending away forward from the subject in the sagittal plane.

Figure 4.2 Pole bending angle of stiff (red) and less stiff (black) poles over a period of five poling cycles during the 10 s test of subject 14 (male). The 180° line represents a pole in its linear state (no bend). Positive bending angles are representative of poles bending away forward from the subject in the sagittal plane.

Video of subjects' 60 s trials was also analyzed to determine the maximum bending angle for each pole type during the longer duration test. Poling cycles were

sampled from seconds 25 to 35 for all subjects and pole types. Mean values for stiff and less stiff pole bending angles are summarized in Table 4.4.

Table 4.4. Descriptive statistics for degrees of pole bending during 60 s UBP tests (Mean $\pm$ SE).

Gender	Maximum bending angle for stiff poles (degrees)	Maximum bending angle for less stiff poles (degrees)
All	1.9 $\pm$ 0.2*	3.2 $\pm$ 0.5*
Male	2.5 $\pm$ 0.2*	4.7 $\pm$ 0.4*
Female	1.3 $\pm$ 0.1	1.5 $\pm$ 0.1

* Denotes significant difference between stiff and less stiff pole bending angles
 Maximum bending angle = average of the maximum pole bending angle, in degrees, from five successive poling cycles.
 Degrees = degrees past 180.

Less stiff poles bent significantly more than stiff poles ($p < 0.001$). Although there was a tendency for women to have greater bending angles with the less stiff poles ($p = 0.084$), only the male subjects exhibited a significant difference between pole types ($p < 0.001$). Figure 4.3 graphically demonstrates the change in bending angle for stiff and less stiff poles over a period of five poling cycles during the 60 s test of subject 1 (female) while Figure 4.4 is the graph for male subject 14. To facilitate direct comparisons between graphs, both figures are displayed with the same x and y scales as Figures 4.1 and 4.2.

Figure 4.3 Pole bending angle of stiff (red) and less stiff (black) poles over a period of five poling cycles during the 60 s test of subject 1 (female). The 180° line represents a pole in its linear state (no bend). Positive bending angles are representative of poles bending away from the subject in the sagittal plane.

Figure 4.4 Pole bending angle of stiff (red) and less stiff (black) poles over a period of five poling cycles during the 60 s test of subject 14 (male). The 180° line represents a pole in its linear state (no bend). Positive bending angles are representative of poles bending away from the subject in the sagittal plane.

The differences between maximum bending angles for stiff and less stiff poles were calculated for the 10 s and 60 s tests (Δflex_{10} and Δflex_{60} , degrees). In addition, the differences between UBP for stiff and less stiff poles were calculated for the 10 s and 60 s tests (ΔW_{10} and ΔW_{60} , W). For each subject, Δflex_{10} and Δflex_{60} were plotted against ΔW_{10} and ΔW_{60} and simple linear regression was used to evaluate correlational relationships. There was no significant relationship between Δflex_{10} and ΔW_{10} ($r = -0.096$) while Δflex_{60} was significantly related to ΔW_{60} ($r = 0.59$). The 10 s test plot contained an outlier that appeared to affect the strength of the correlation. After removal of this data point, Δflex_{10} was significantly related to ΔW_{10} ($r = 0.62$). Figure 4.5 shows Δflex_{10} plotted against ΔW_{10} and Figure 4.6 shows Δflex_{60} plotted against ΔW_{60} .

Figure 4.5. Linear relationship between pole bending (Δflex_{10}) and differences in UBP output (ΔW_{10}) from the 10 s test. Open circle represents subject excluded from subsequent analysis. Line is best fit line for all subjects ($n = 14$) ($\Delta\text{flex}_{10} = 0.840 + 0.074 \cdot \Delta W_{10}$; $r = 0.62$).

Figure 4.6. Linear relationship between pole bending (Δflex_{60}) and differences in UBP output (ΔW_{60}) from the 60 s test. Line is best fit line for all subjects ($n = 15$) ($\Delta \text{flex}_{60} = 0.937 + 0.055 \cdot \Delta W_{60}$; $r = 0.59$).

Subjects' values for Δflex_{10} (degrees) were also plotted against their absolute UBP (W, stiff pole condition) from the 10 s test and values for Δflex_{60} (degrees) were plotted against absolute UBP (W, stiff pole condition) from the 60 s test. Differences in flex had a strong correlation to absolute UBP for both 10 and 60 s tests ($r = 0.76, 0.88$ for 10 and 60 s tests, respectively). However, observation of the plots revealed that variance of Δflex values from the line of best fit was greater with the highest power outputs for both 10 and 60 s tests (Appendix B). A logarithmic transformation is a common technique used on physiological data to make variances more comparable across subjects (i.e., homoskedasticity). This transformation yielded stronger correlations between pole bending and absolute UBP ($r = 0.86, 0.94$ for 10 and 60 s tests, respectively). Figure 4.7 shows logarithmic transformations of Δflex_{10} plotted against W_{10} (stiff poles) and figure 4.8 shows logarithmic transformations of Δflex_{60} plotted against W_{60} (stiff poles).

Figure 4.7. Linear relationship between Log_{10} transformed pole bending (Δflex_{10}) and absolute UBP output using stiff poles ($W_{10, \text{stiff}}$) from the 10 s test. Line is best fit line for all subjects ($n = 15$) ($\Delta \text{flex}_{10} = -4.256 + 1.838 \cdot W_{10}$; $r = 0.86$).

Figure 4.8. Linear relationship between Log_{10} transformed pole bending (Δflex_{60}) and absolute UBP output using stiff poles ($W_{60, \text{stiff}}$) from the 60 s test. Line is best fit line for all subjects ($n = 15$) ($\Delta \text{flex}_{60} = -4.104 + 1.783 \cdot W_{60}$; $r = 0.94$).

CHAPTER 5

DISCUSSION

Many studies have shown the importance of upper body power (UBP) in cross-country ski performance (Gaskill et al., 1999; Hoff et al., 1998; Mahood et al., 2001). For example, Alsobrook (2005) determined that different measures of UBP, such as 10 s and 60 s maximal tests along with maximum power (during a test to exhaustion) all correlate highly with actual race performance and with each other. Thus, each test is a valid predictor of ski performance. The present study is the first to determine if measures of UBP could be affected by the stiffness of the ski pole shaft. It is important to note that the two types of poles used in the study were both high quality race poles (The stiffer pole was 1.3 times stiffer and 19 g/m lighter; Swix Sport, 2008). The focus of this study, therefore, was to determine if significant differences in UBP could be determined when comparing race poles of similar quality, as opposed to testing a race pole against a largely inferior pole.

Measures of Upper Body Power

Each subject tested two types of ski poles (“stiff” and “less stiff”) on a double poling ergometer. Differences in UBP measures were determined by a 10 s (W_{10} , W) and a 60 s (W_{60} , W) maximal test. Also, since the degree of pole flex is due to the amount of power applied and is not directly affected by a skier’s body mass; UBP was expressed as an absolute value. Values for W_{10} were 255 ± 32 W and 248 ± 30 W for stiff and less stiff

poles, respectively, while mean values for W_{60} were 208 ± 24 W and 201 ± 22 W. There was a tendency for subjects to have higher W_{10} and W_{60} values with the stiff poles ($p = 0.077$ in both cases). After data for the two tests were collected, it was determined that results should be grouped by gender for statistical analysis due to the large differences in power output between men and women. Mean UBP for men's W_{10} was 358.1 ± 21.3 W and 345.6 ± 21.9 W for the stiff and less stiff poles, respectively, while mean UBP for women's W_{10} was 136.9 ± 9.1 W and 136.1 ± 6.3 W. Upper body power output for W_{10} was not significantly different between pole types for women ($p = 0.837$), though there was a tendency for men to have higher W_{10} values using the stiff poles ($p = 0.066$). Mean UBP for men's W_{60} was 286 ± 14.1 W and 272 ± 14.1 W for stiff and less stiff poles, respectively, while mean UBP for women's W_{60} was 117.7 ± 7.0 W and 120.1 ± 6.6 W. Upper body power values for women, which were less than half that of males tested, did not differ with pole type ($p = 0.315$). However, men had significantly higher UBP values for W_{60} when using stiff poles ($p = 0.014$). Thus, ski pole stiffness only influenced UBP over a 60 s maximal effort for the most powerful skiers.

Gaskill et al. (1999) compared absolute UBP of subjects from a wide range of ages and ski abilities. Significant differences were revealed between males (193.9 ± 85.1 W) and females (116.0 ± 59.6 W), along with several subgroups including adult males (253.7 ± 58.9 W) and females (179.2 ± 57.2 W), high school males- fast (231.1 ± 68.3 W) and slow groups (115.3 ± 49.8 W), and high school females- fast (145.4 ± 36.3 W) and slow groups (62.2 ± 23.7 W). The protocol for determining UBP was a graded double-pole ergometer test of increasing resistance. Each level was 20 seconds in

duration, during which the subject maintained a resistance flywheel cadence of 350 rpm. The test ended when subjects could no longer maintain the necessary RPMs. Although the protocol is different than that used in the present study, the 20 s time period is between the duration of the 10 s and 60 s maximal tests used herein. There are many subgroups in the Gaskill study with UBP values that fall in between W_{10} and W_{60} values for the males and females in the present study. Future research on pole stiffness should include a similar spectrum of abilities to those in the Gaskill study in order to determine the power output at which pole stiffness becomes a significant determinant of UBP.

Measures of Ski Pole Bending

Pole bending was determined by analyzing video from the 10 and 60 s tests. Subjects created significantly larger pole bending angles with less stiff poles than with stiff poles during the 10 s test. However, after analyzing by gender, only male subjects had significantly greater pole bending angles with the less stiff poles. Although not significant, there was still a tendency for women to create greater bending angles with the less stiff poles. Subjects also created significantly larger pole bending angles with less stiff poles than with stiff poles during the 60 s test. Again, only male subjects showed any significant differences after analyzing by gender. Although not significant, there was a tendency for women to create greater bending angles with the less stiff poles compared to the stiff poles. The maximum bending angle for less stiff poles was much higher for men than women from both the 10 s (6.3 ± 0.7 versus 1.6 ± 0.2 W for men and women, respectively) and 60 s tests (4.7 ± 0.4 versus 1.5 ± 0.1 W for men and women,

respectively). Furthermore, the pole bending angles for stiff poles from men's 10 s and 60 s tests (3.0 ± 0.2 and 2.5 ± 0.3 W for $W_{10,\text{stiff}}$ and $W_{60,\text{stiff}}$, respectively) were higher than the bending angles exhibited by women with the less stiff poles (1.6 ± 0.2 and 1.5 ± 0.1 W for $W_{10,\text{less stiff}}$ and $W_{60,\text{less stiff}}$, respectively). Male subjects were also able to create greater bending angles over the course of the 60 s tests than females could achieve with less stiff poles during the much shorter duration 10 s tests (2.5 ± 0.2 versus 1.6 ± 0.2 W for men $W_{10,\text{stiff}}$ and Women $W_{60,\text{less stiff}}$). Although no statistical analysis was computed for these comparisons, it is clear that the male subjects were bending the stiff ski poles more than the women could bend the less stiff poles. It is not surprising, therefore, that significant differences in pole bending and UBP were only found in male subjects. Significant differences in bending between pole types for male subjects as well as the large gap between men's and women's UBP further indicate that a certain power threshold must be reached for pole stiffness to affect power output.

Gender Differences in Upper Body Power and Pole Bending

Mean power output values for women were less than half of those for men in both W_{10} and W_{60} . The large gender gap in UBP is not likely due to the women's lack of ability since at least one subject was competing internationally and many others were highly ranked in the U.S. To achieve a specific skiing speed, a smaller individual will have to produce less absolute power than a larger individual. Therefore, even though many of the female subjects were skiers of a high caliber, their generally small stature could limit the absolute power output. It is possible that many women were not able to

create enough power to cause pole bending that would affect UBP measures for either pole type.

Although a gender gap was expected, the difference in power output was approximately 80 W larger than reported by Alsobrook (2005). It is possible that the men participating in the present study were of a higher ability level, on average, than those previously tested. Women from the present study were similar in UBP to values reported by Alsobrook (2005). However, men in the present study, averaging 358 W and 286 W for 10 s and 60 s tests, respectively, were much more powerful than those tested by Alsobrook (2005), who averaged 275 W and 210 W for 10 s and 60 s tests. One difference between the protocol of the Alsobrook (2005) study was the use of a single resistance setting (1 for all subjects, ergometer has a resistance setting from 1 to 10) versus a mixed resistance protocol for the present study (1 for women, 8 for men). Observational pilot studies revealed that the ergometer needed to be on the lightest resistance setting for women to not fatigue during the course of the entire test protocol. A ski pole bends in reaction to forces from the skier in addition to a reactionary force from the ground. In real world conditions, this ground reaction force would equal the force supplied by the skier. However, the reactionary forces from the low ergometer resistance may not have been high enough to create a bend in the pole. Thus, even though there was no significant difference in UBP or pole bending detected in the ergometer test, these same poles may have an affect on women's UBP in real world conditions.

Another factor that could influence the amount of pole bending, and subsequently UBP, is the length of poles used. When considering the cause of pole bending it is

important to note that men, on average, are taller and thus will use longer poles. Male subjects in this study used poles between 150 and 160 cm in length, while female subjects used either 140 or 145 cm poles. A force applied perfectly longitudinal to the pole could be continually increased, with no sign of flexing, until the pole shaft deformed or broke. This would be a true test of the poles' stiffness. However, it is nearly impossible to apply forces in such a perfect manner when skiing. In addition to force being applied longitudinally to the pole, there is usually enough force being applied perpendicular to the pole to create a bend. The resulting force vector is oriented slightly more perpendicular to the ground than the pole itself. Furthermore, poles of different lengths are similar in composition that it can be assumed when a force is applied perpendicular to the pole, its deflection will increase proportionally in relation to pole length. Therefore, a 160 cm pole (the longest used in the study) will bend more than a 140 cm pole (the shortest used) in reaction to an equal force vector. Also, men using poles in the 150-160 cm range were exerting much greater power than women who used poles in the 140-145 cm range. Thus, affects from pole length on measures of pole bending and UBP may have been further amplified.

Correlations between Upper Body Power and Pole Bending

The difference between each subject's power output using the stiff and less stiff poles was calculated for both test lengths (ΔW_{10} and ΔW_{60} , W). Differences in each pole type's maximum bend angle were also calculated for both tests (Δflex_{10} and Δflex_{60} , degrees). Initially, no correlation was found between differences in pole bending

(Δflex_{10}) and changes in power output (ΔW_{10}) for the 10 s test ($r = -0.096$). However, after the elimination of an outlier, the two factors were strongly correlated with one another ($r = 0.62$). Differences in pole bending during the 60 s test (Δflex_{60}) were strongly correlated with changes in UBP (ΔW_{60}) as well ($r = 0.59$). Therefore, increased pole bending was linked to decreased UBP for 10 and 60 s tests.

Differences in pole bending were also plotted against the absolute power values of subjects using stiff poles during the 10 and 60 s tests ($W_{10,\text{stiff}}$ and $W_{60,\text{stiff}}$, W). A logarithmic transformation of the data yielded very strong correlations for both Δflex_{10} versus $W_{10,\text{stiff}}$ ($r = 0.86$) and Δflex_{60} versus $W_{60,\text{stiff}}$ ($r = 0.94$). Thus, subjects with the highest power outputs were likely to experience the greatest pole bending, along with a significant loss of power for 10 and 60 s tests. Correlational relationships were determined using values for all subjects; however it is possible that power output affects the male and female groups differently. It is assumed herein that although there is a gap between female and male data points, they are representative of a continuum for which a population exists (but was not tested in the present study) that fills the gap.

Most male subjects had higher UBP when using the stiff poles while one subject recorded higher W_{10} values with the less stiff poles and a different subject registered a slightly higher W_{60} value with less stiff poles. The subject with the abnormal W_{10} value could be explained by inter-subject test variations due to problems with the 10 s test protocol. It appeared that the 10 s UBP test was easily influenced by the protocol-scheduled build-up of effort that preceded the 10 seconds of maximal effort. Successive W_{10} trials could vary as much as 44 W for one pole type, most likely due to the amount of

momentum carried over from the preceding build-up. Although Alsobrook (2005) showed the 10 s test to be a valid predictor of ski performance, it may not be reliable enough for the present study.

The subject with higher W_{60} values with the less stiff poles could be explained by an overly conservative pacing strategy. The 60 s test is highly strenuous and requires some pacing at the start. Even with pacing, a subject's maximal effort is evidenced by continuously dropping power values at the end of the test. However, an investigation into the test in question showed equal power values for the final fifty seconds of the test (the average values of the first ten seconds were lower; due to the time needed to build up to the desired intensity). Furthermore, ten second averages for the stiff and less stiff poles were exactly the same. Thus, the subject employed the same pacing tactics for both tests and likely did not reach maximal exertion for either trial.

Performance Effects from Pole Design

Besides stiffness, another quality that makes higher end poles desirable is their light weight. Although both poles used in this study were high quality race poles, the stiff poles were approximately 30 g lighter than the less stiff poles. Therefore, women and other skiers with lower UBP (e.g. junior or master skiers) who receive no significant advantage from slight differences in pole stiffness may still desire the stiffest poles for the weight savings. Although it is not known exactly how much these weight savings would affect performance, using an estimation technique that Street (1992) derived from studies on load carriage and energy expenditure in skiers, the advantage gained by the 30

g weight difference was calculated to be ~1.5 seconds over a course of 20 km (Rundell & Szmedra, 1997; Saibene, Cortilli, Roi, & Colombini, 1989; Taylor, Heglund, Thomas, & Looney, 1980). Furthermore, studies of loads carried in the hands suggest that the advantage could be as little as one second for a 20 km course (Saibene et al., 1989; Soule & Goldman, 1969). A study by Hartner et al. (1991) lends more evidence to the insignificance of minor differences in pole design during longer bouts. The authors determined there was no difference in energy expenditure between four different ski pole grips during an eight minute, submaximal double-pole ergometer test. It is impossible to theorize if the stiff poles used in this study would be advantageous over the course of a 20 km time trial because all tests were of maximal effort and not applicable to a hour-long submaximal effort.

Although a single second can determine the outcome of a 20 km time-trial race, it is unlikely that the weight savings could influence the sprint finish of mass start events. Maximal power output, on the other hand, would be a key factor in such an event. In another ski pole grip study, Heil et al. (2004) proved that differences in equipment can have an impact on UBP during a shorter duration test of 10 s. Of three racing grips tested, subjects were able to record significantly higher power outputs with one of the grip designs. While no attempts were made to correlate ski pole stiffness to race performance in the present study, Alsobrook (2005) derived an estimation equation using a correlation of subjects' 10 s (W_{10} , W) and 60 s (W_{60} , W) UBP tests with race speed (m/s).

$$\text{Race speed} = 3.35 + 0.007 \cdot W_{10}$$

$$\text{Race speed} = 3.29 + 0.01 \cdot W_{60}$$

Using the W_{60} equation, it was estimated that competitors at maximal effort during the last minute of a mass start race could gain up to four seconds using the stiffer poles.

Another factor that is desirable to ski racers is the “swing weight” of a pole. A decreased swing weight (moment of inertia) is due to weight reduction at the distal end of the pole and gives the impression of using less energy to swing the poles forward. Street (1992) stated that weights of 10-20 g at the tip of a ski pole can increase the moment of inertia by 32-49%. These large differences are easily discernable when skiing and swing weight is a common selling point for ski pole manufacturers (Swix Sport, 2008). Higher-end poles are designed to have reduced less swing weight but, again, it is unknown if this factor has any significant affect on performance.

Future Studies of Pole Stiffness

Due to the possible confounding factor of ergometer resistance, future studies should incorporate field tests on snow or with rollerskiing in order to more accurately reflect ground reaction forces encountered while skiing. Although there is no linear correlation between pole bend and UBP, there is a link between the ability to significantly bend less stiff poles and the ensuing loss of power. Women, who exhibited no significant differences in the lab setting, may be able to bend the less stiff poles in an on-snow test or while rollerskiing. Due to the low rolling resistance of rollerskis, it is recommended that the speeds at maximal efforts are controlled by running field tests

uphill. Inclined courses would also cause subjects to increase poling forces and may help to expose differences due to pole stiffness (Millet et al., 1998b). The obvious choice for future testing protocols would be a 1 km up hill double-pole time trial, due to its validity as a predictor of performance (Mahood et al., 2001; Rundell & Bacharach, 1995). For on-snow and rollerski trials, time to complete a standard course length would be the dependant variable instead of power output (W). Also, short maximal tests may prove more reliable on snow or rollerskis than on the ergometer used in this study. In order to minimize effects from changing snow conditions on-snow tests would only be feasible if all subjects were able to test in a short period of time on the same day. However, one drawback to a one-day on-snow study would be the reduction of trials to ensure fatigue would not be a confounder.

CHAPTER 6

CONCLUSION

The findings of this study indicate that differences in pole stiffness can affect measures of upper body power (UBP) in skiers with the highest power outputs. Subjects produced significantly greater poling angles with less stiff poles and, although not significant, there was a trend for lower UBP values with less stiff poles. When analyzed by gender, only male subjects produced significantly greater bending angles and lower UBP (60 s test only) with less stiff poles. Although not significant, male subjects also had a tendency to have lower UBP in the 10 s test with less stiff poles. It is possible that the 60 s test is a more reliable measure of UBP.

Although there were no significant differences in pole bending or UBP for female subjects, it is important to note that the two pole types being compared were both high-end race poles. Differences, although not significant, were still seen for female subjects and it is likely that skiers with lower UBP (e.g., women, master, junior skiers) could experience reduced power output when using less stiff poles than those tested in the present study.

The difference in bending angles between the stiff and less stiff poles was highly correlated with UBP for both the 10 s and 60 s tests. It appears that the very highest quality ski pole (the stiff pole used in the present study) would only benefit those with the highest UBP outputs. In the present study, there was a large gap in UBP between men and women for both the 10 s and 60 s tests. Considering that only male subjects exhibited

any significant differences between pole types, the point at which pole stiffness can affect UBP likely resides within this gap. Therefore, future studies should attempt to test skiers of a larger range of ability. Due to differences in ergometer and real-world conditions, future studies should also examine the effects of pole stiffness in rollerski or on-snow trials.

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APPENDICES

APPENDIX A:
SUBJECT CONSENT FORM

**SUBJECT CONSENT FORM
FOR PARTICIPATION IN HUMAN RESEARCH
MONTANA STATE UNIVERSITY**

PROJECT TITLE: *Effect of Ski Pole Stiffness on Upper Body Power Output in Cross-Country Skiers*

PROJECT DIRECTOR: Erik Jacobson, Graduate Student
Dept. of Health and Human Development, Movement Science Laboratory
Montana State University, Bozeman, MT 59717-3540
Phone: (307) 399-4364
E-mail: nordicpunk@yahoo.com

FUNDING: This project is not funded

PURPOSE OF THE STUDY:

The purpose of this study is to determine how measures of upper body power (UBP) are affected by pole stiffness when cross-country skiing. Each subject will perform a series of tests on a modified rowing ergometer. The ergometer consists of a large air resisted flywheel connected to an 8-foot long I-beam. Subjects will stand on a platform at the point where the beam connects to the flywheel. A resistance loaded trolley runs along the beam and is connected to the flywheel with static cord. The subjects will push the trolley down the track with attached ski poles. Two sets of poles of differing longitudinal stiffness will be supplied for each test by the researcher. Upper body power (W) is measured by the ergometer during tests of 10 and 60 seconds in duration. The intent of these trials is to detect any changes in the measurements due to the stiffness of poles used. These findings could provide useful information for coaches, and you, as an athlete, to understanding how pole stiffness can affect ski performance.

Each participant is presented with this *Informed Consent Document* which explains the purpose of the testing, as well as expected risks and benefits associated with participation. It is the participant's responsibility to acquire medical clearance from his/her physician prior to lab testing. Each participant will also be screened by the project director using responses provided by participants in the **Health History Questionnaire** (the Health History Questionnaire is attached to the end of this document). This procedure is in compliance with policies formulated by the American College of Sports Medicine¹.

Please talk with the Project Director, Erik Jacobson, about any pre-existing health conditions that may limit your participation in this project *BEFORE* testing.

STUDY PROCEDURES:

You (the participant) will be required to make three visits to the Movement Science / Human Performance Lab (basement of Romney Building) within a one month period. The first visit will last approximately 45 minutes and will be scheduled no sooner than 24 hrs after your last hard workout. *If you use an inhaler to treat asthma, be certain to bring the inhaler with you to the lab.*

¹American College of Sports Medicine (2006). *ACSM's Guidelines for Exercise Testing and Prescription* (7th edition). Lea & Fibiger; Philadelphia, PA.

You should arrive at the lab ready to engage in high intensity ski-bounding (running with ski poles). Therefore, you should dress in running shoes and lightweight, breathable garments suitable for running. You should eat, and drink fluids appropriately for the occasion. You should also know the approximate size of ski poles you use for classic style skiing. The second and third visit will last approximately 30 minutes. You should again dress for running and eat appropriately for the occasion. You should arrive at the lab ready to engage in moderate intensity double pole skiing on the ergometer). *Again, if you use an inhaler to treat asthma, be certain to bring the inhaler with you to the lab.*

Session #1- VO_{2max} Testing

VO_{2max} Testing: The VO_{2max} protocol is necessary to collect demographic information of the test population. The VO_{2max} test is an incremental graded test to exhaustion on a treadmill designed to determine the maximal amount of oxygen consumption that you are capable of. Oxygen consumption will be measured constantly during the test with a metabolic system. Height, weight, sex, and age will be recorded before the testing and you will be fitted with a heart rate monitor. You will be allowed to warm up on the treadmill before the test begins. The purpose of the warm is not only to warm up the body, but also to familiarize your self with the treadmill and starting and stopping safety procedures. The protocol begins with 3 min stages of increasing speed and grade. Each stage will be followed by fingertip blood lactate sampling with the treadmill stopped until a steep increase in blood lactate concentration is seen (lactate threshold). After a blood lactate spike is observed, the stages will shorten in duration to 1 min without lactate testing and will continue to increase in speed and grade until volitional exhaustion is reached. The test will provide measures of maximum oxygen consumption, maximum heart rate, and lactate threshold.

Session #2,3- Ergometer Testing and Video

Upper Body Power Testing: The Upper body power (UBP) test will consist of 3 trials lasting 30 s in duration and 1 trial lasting 60 s. The 30 s trial begins with 10 s of easy poling. The next 10 s are intended for you to ramp up speed in preparation for the final 10 s, which are maximal effort. The value for UBP will be determined by averaging the power measurements (W) from the final 10 s. You will be allowed to rest in between the 3 UBP trials. The value from the 60 s power test will be calculated as the average of all power values from the full 60 s.

Video Recording: Sessions 2 and 3 will be video recorded in an attempt to visually measure the difference in pole stiffness. The less stiff pole shaft will deflect laterally under downward force. Reflective markers will be placed at the top, middle, and bottom of the pole nearest the video camera and on body joints in the sagittal plane. When force is applied to the pole during testing, the middle of the pole deflects outward and the markers create the three points of an angle. Thus the angle can be measured and the stiffness of the two different pole shafts can be compared. Reflective markers will also be placed on both the upper body (e.g. wrist, elbow, shoulder joint) and the lower body (e.g., hip joint and knee joint) to document how the double-poling movement pattern may change with pole stiffness.

POTENTIAL RISKS:

You should be aware that all of the tests may cause extreme fatigue immediately after the tests and possibly during the next day. VO_{2MAX} testing (ie. treadmill protocol) also involves a chance of precipitating a cardiac event (such as abnormal heart rhythms) or even death. However, the possibility of such an occurrence is very slight (less than 1 in 10,000) since 1) you are in good physical condition with no known symptoms of heart disease and 2) the test will be administered by trained personnel (American Red Cross CPR certified and aware of the lab's emergency action plan). *These risks are certainly no greater than those experienced by trained athletes in*

actual race competition. The measuring devices (heart rate monitor and mouthpiece for $\text{VO}_{2\text{MAX}}$) may feel somewhat restricting and/or uncomfortable during testing, but all possible adjustments will be used to achieve the greatest comfort for you. All possible precautions will be taken to ensure your safety and make you feel comfortable before any testing takes place.

BENEFITS:

You will receive personalized feedback on your $\text{VO}_{2\text{max}}$ and lactate threshold. Additionally, study participants may request a summary of the study findings by contacting the Project Director, Erik Jacobson, by phone (307-399-4364) or by e-mail (nordicpunk@yahoo.com).

CONFIDENTIALITY:

The data, video, and personal information obtained from this study will be regarded as privileged and confidential. Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Your right to privacy will be maintained in any ensuing analysis and/or presentation of the data by using coded identifications of each person's data. The code list will be kept separate and secure from the actual data files.

FREEDOM OF CONSENT:

Participation in this project is completely voluntary. You may withdraw consent for participation in writing, by telephone, or in person without prejudice or loss of benefits (as described above). Please contact the Project Director, Erik Jacobson, by phone (307-399-4364) or by e-mail (nordicpunk@yahoo.com) to discontinue participation.

In the UNLIKELY event that your participation in the project results in physical injury to you, the Project Director will advise and assist you in receiving medical treatment. No compensation is available from Montana State University for injury, accidents, or expenses that may occur as a result of your participation in this project. Additionally, no compensation is available from Montana State University for injury, accidents, or expenses that may occur as a result of traveling to and from your appointments at the Movement Science / Human Performance Laboratory. *Further information regarding medical treatment may be obtained by calling the Project Director, Erik Jacobson, at 307-399-4364.* You are encouraged to express any questions, doubts or concerns regarding this project. The Project Director will attempt to answer all questions to the best of their ability prior to any testing. The Project Director fully intends to conduct the study with your best interest, safety and comfort in mind. *Additional questions about the rights of human subjects can be answered by the Chairman of the Human Subjects Committee, Mark Quinn, at 406-994-5721.*

I, *the participant*, have read the Informed Consent Document and understand the discomforts, inconvenience, risks, and benefits of this project. I, _____ (*print your name*), agree to participate in the project described in the preceding pages. I understand that I may later refuse to participate, and that I may withdraw from the study at any time. I have received a copy of this consent form for my own records.

Witness: _____ Date _____
Print Name *Sign Name*

APPENDIX B:

SUBJECT POLE LENGTHS AND ERGOMETER RESISTANCE SETTINGS

Table B.1. Subject pole length and ergometer resistance setting.

Subject	Gender	Pole length (cm)	Ergometer resistance setting (1-10)
1	0	145	1
2	1	155	8
3	1	160	8
4	0	140	1
5	1	155	8
6	0	140	1
7	1	150	8
8	0	140	1
9	0	145	1
10	0	145	1
11	1	155	8
12	0	145	1
13	1	155	8
14	1	160	8
15	1	160	8

Gender: 0 = female, 1 = male

APPENDIX C:

SCATTERPLOTS OF Δ FLEX VERSUS ERGOMETER MEASURES

Figure C.1. Linear relationship between pole bending ($\Delta flex_{10}$) and absolute UBP output using stiff poles ($W_{10, stiff}$) from the 10 s test. Line is best fit line for all subjects ($n = 15$) ($\Delta flex_{10} = -0.6422 + 0.009 \cdot W_{10, stiff}$, $r = 0.76$).

Figure C.2. Linear relationship between pole bending ($\Delta flex_{60}$) and absolute UBP output using stiff poles ($W_{60, stiff}$) from the 60 s test. Line is best fit line for all subjects ($n = 15$) ($\Delta flex_{60} = -0.940 + 0.010 \cdot W_{60, stiff}$, $r = 0.88$).