

Warm-up: Efficacy of a program designed for downhill skiing

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A warm-up program designed for downhill skiers and conducted in alpine conditions was tested for its effectiveness in "warming up" the body prior to participation in 90 minutes of downhill skiing. Eight subjects were randomly allocated and participated in both the warm-up and control conditions. Measurements were taken of rectal temperature, skin temperature, heart rate and flexibility prior to warm-up, immediately post-warm-up/immediately pre-skiing, and at 15min intervals during 90 minutes of skiing. The main analyses used were planned contrasts on repeated measures analysis of variance. Participation in the warm-up program resulted in significant increases in: rectal temperature ($F_{(1,6)} = 8.196$; $p = 0.008$); heart rate ($F_{(1,7)} = 32.97$, $p < 0.001$); and flexibility ($F_{(1,6)} = 10.14$, $p = 0.003$) when compared with the control condition. These findings demonstrate that the program was effective in warming up the body. [Whelan KM, Gass EM and Moran CC (1999): Warm-up: Efficacy of a program designed for downhill skiing. *Australian Journal of Physiotherapy* 45: 279-288]

Key words: Body Temperature; Exercise; Heart Rate; Skiing

Introduction

Warm-up programs conducted prior to participation in sport are recommended in the literature as a strategy in the prevention of injuries (Bixler and Jones 1992, Jendrusch et al 1994, Robergs et al 1991, Williams et al 1996). The physiological effects of a warm-up program designed specifically for downhill skiing have not been reported in the literature. This information would aid the understanding of the underlying mechanisms by which warming up may achieve its effects.

Warm-up has been defined as an activity that raises total body temperature, as well as the temperature of the muscles, to prepare the body for vigorous exercise (Anderson and Burke 1991, p. 65). The term can also encompass a broader meaning as described by Safran et al (1988, p. 123): The warm-up period often consists of both stretching exercises and a period of active muscle contraction or exercise. A warm-up period should increase the range of motion of the joint and muscle-tendon units as well as increase the muscle temperature and the efficiency of the muscle contractions.

Factors affected by warm-up Deep body temperature, muscle temperature, skin temperature

(Tsk), and heart rate (HR) are reported to be increased by warm-up, as they are by general exercise (Astrand and Rodahl 1986, Chwalbinska-Moneta and Hanninen 1989). These changes result in increases in oxygen consumption (O'Brien et al 1997), metabolic rate, removal of metabolic by-products, and nerve conduction (Astrand and Rodahl 1986, Shellock and Prentice 1985). The acceleration of metabolic rate promotes the efficient use of substrates that are vital for providing the energy that is necessary for physical activity. The overall effect is that physical performance is enhanced in the form of increased power (O'Brien et al 1997) and speed (Astrand and Rodahl 1986).

Warm-up, like general exercise, produces an increased blood flow to the active muscles and decreased flow to the viscera (Shellock and Prentice 1985). The delivery of necessary substrates is therefore increased and the mechanical efficiency of the contracting muscles is enhanced by a reduction in muscle protoplasm viscosity (Ciullo and Zarins 1983, Rosenbaum and Hennig 1995, Shellock and Prentice 1985). It has been suggested that higher tissue temperatures enhance joint range of motion and flexibility by increasing the extensibility of tendons, ligaments and other connective tissues (Sapega et al 1981, Williford et al 1986).

Measurements of warm-up Rectal temperature (Tre) has been demonstrated to be a reliable and commonly used measure of deep body temperature (Gillette et al 1991, O'Brien et al 1997, Robergs et al 1991). Skin temperature is commonly measured to provide additional information about body temperature changes. Up to 10 standard sites are normally used for thermistor placement and include the head, chest, upper back, lower back, abdomen, upper arm, forearm, hand, thigh, and calf (Chwalbinska-Moneta and Hanninen 1989, O'Brien et al 1997). Heart rate is also commonly measured, since it is an indicator of cardiovascular function and physiological stress (Gillette et al 1991, O'Brien et al 1997, Robergs et al 1991, Rosenbaum and Hennig 1995). The sit-and-reach test as described in Harris (1969) is a simple and quick measure of general flexibility that is widely used (Hoeger and Hopkins 1992) because it is influenced by spinal and hip joints and a variety of associated muscle and soft tissue structures (Kapandji 1974, Matyas and Bach 1985). All of these measurements would appear to be useful since they provide a variety of information regarding the physiological effects of warming up.

The purpose of this study was to determine whether a warm-up program conducted on the snow and designed to prepare skiers for downhill skiing, did in fact warm up the body.

Methods

This study was approved by The University of Sydney Human Ethics Committee.

Subjects Eight subjects (six intermediate and two advanced skiers) participated in both of the conditions, warm-up and control. Intermediate downhill skiing ability was defined as parallel skiing on moderate slopes at moderate speeds, while advanced downhill skiing ability was defined as parallel skiing on all slopes at high speeds. Seven of the subjects were male and one subject was female. The mean age of the group was 33.25 (7.6, SD) years (range = 24-48).

Source and means of recruitment of subjects The nature of the study required the use of a sample of convenience (ie subjects were not randomly selected). Potential subjects who were known to the investigators as friends or colleagues were contacted

and invited to participate. All participants provided informed written consent.

Exclusion criteria Subjects were to be excluded from the study on the basis of the following criteria: less than 18 years of age or greater than 50 years; beginner skiers; pregnancy; fever or illness; physical disability that would interfere with downhill skiing; and unhealthy subjects. None of the recruited subjects needed to be excluded.

The warm-up program The warm-up program was designed to prepare the skier specifically for downhill skiing. It was based on a pilot study of the warm-up program conducted in a thermoneutral laboratory. In the pilot study, six subjects performed the warm-up program on carpet using their ski boots, skis and poles and dressed in shorts and a t-shirt. The study demonstrated significant increases in Tre and HR. These increases were maintained for 30 minutes post-warm-up.

The warm-up program consisted of a combination of appropriate general exercises to stimulate the cardiovascular system, stretches of relevant muscles to improve flexibility and skiing specific exercises to activate the same muscles and replicate movements that are used for skiing (Shellock and Prentice 1985, Wilson et al 1991) (Appendix 1). Generally, the stretches included in the warm-up program were held for 20 seconds (Madding et al 1987, Taylor et al 1990) and repeated twice to each side. Subjects were instructed to perform the stretches so that they felt a sensation of moderate pull without pain (Taylor et al 1990). Based on a study reported by Whelan (1996) of injured downhill skiers who sustained injuries to the spine and upper limbs as well as the lower limbs, the exercises and stretches were designed to involve all of these areas.

The program duration was 16.5 minutes at an intensity of approximately 60 per cent of maximum HR (Borg Scale for Rating of Perceived Exertion of 11-12) (Borg 1971). The warm-up program was designed to be intense enough to increase body temperature in the cold alpine environment, but not so intense as to cause fatigue (Astrand and Rodahl 1986). The results of the pilot study indicated that the warm-up program appeared to satisfy these criteria. The warm-up program was instructed and supervised to ensure that all subjects underwent the same program.

Measurements Portable systems were used to measure ambient temperature and wind velocity, Tre, Tsk, HR, and sit-and-reach flexibility. In order to minimise measurement error, all temperature measurement equipment was calibrated before and after testing in water tanks of known temperatures.

Measurement of deep body temperature was via a thermocouple (AD590) inserted by each subject approximately 12cm past the anal sphincter into the rectum and taped securely on the skin. Skin temperature was measured by thermocouples (AD590) taped onto the skin surface after the skin had been shaved (if necessary) and wiped with alcohol. Three standard sites were used: left upper chest, left mid lateral thigh, and left mid lateral calf (Chwalbinska-Moneta and Hanninen 1989, O'Brien et al 1997). All leads from recording equipment were securely taped just inside the front of each subject's ski jacket. These were easily accessible for subsequent recordings.

Heart rate was measured by two electrocardiograph (ECG) Sport Tester electrodes fitted to a belt that was strapped around the chest by one of the investigators after the skin had been shaved (if necessary) and wiped with alcohol. The receiver was in the form of a watch strapped to the wrist of one of the investigators.

Flexibility was measured with the sit-and-reach test (Harris 1969). This is an efficient measure of general flexibility, which is an important factor considering the cold alpine environment in which these measurements would take place. Subjects were wearing rigid ski boots which maintained the ankle in a constant position. The subject sat on the ground in long sitting with the legs together and knees extended and was asked to reach towards the toes as far as possible and comfortable, with the elbows extended. One of the investigators placed their hands underneath the subject's knees. As soon as the knees were felt to rise, the subject was asked to hold that position while the other investigator measured the distance between the subject's longest finger and the sole at the toe of the ski boot. These two investigators maintained the same measurement duties throughout the study.

Dry and wet bulb ambient temperatures were measured using a sling psychrometer (Zeal, England). Air flow was measured with an anemometer (ETA 3000, Airflow Development, England).

Study design A single group repeated measures 2 x 4 factorial design (with two repeated measures factors) was used. The first factor represented the experimental condition with two levels, warm-up and control. In the warm-up condition, subjects participated in a warm-up program prior to downhill skiing, whereas in the control condition, they participated in downhill skiing only. The second factor represented the measurement occasions which were analysed within each condition, that is, baseline, immediate post-warm-up, 30 minutes of skiing, and 90 minutes of skiing.

One or two experimental subjects participated in the study at the same time as one or two control subjects. Subjects were randomly assigned to one of the conditions on Day 1 and participated in the other condition on Day 2, at a similar time of day, in order to minimise effects of variations in diurnal temperatures.

Statistical considerations a) Data analysis: The main analyses used were planned contrasts on repeated measures ANOVA (Hays 1988) to test specific comparisons among means in the data. There were two basic types of statistical comparisons. Firstly, comparison of means over time (eg pre-warm-up compared with post-warm-up and during skiing), and secondly, comparison across conditions (eg warm-up compared with no warm-up). These tests were conducted on the Super ANOVA V.1, 11 Macintosh, 1989-1991, Abacus Concepts, Inc. computer program.

b) Error rates: The control of Type I error rate was set at alpha (α) = 0.05. In this study, the contrasts were not orthogonal (ie not independent), and since they tested related hypotheses, the Type I error rate may have been related and inflated across these tests. To control for this, each planned contrast was tested against $\alpha = 0.05/\text{number of comparisons}$ (eg $\alpha = 0.05/3 = 0.0167$), giving an overall nominal Type I error rate for each set of multiple comparisons. This ensured that the maximum Type I error rate for any contrast set tested should not exceed 0.05. Taking precautions over the Type I error rate can increase the Type II error rate. Therefore, both significance levels at the adjusted rate (ie $p < 0.001$) and also those results that only achieve significance at the less conservative value (ie $p < 0.05$) have been reported. No additional controls were taken based on the number of dependent variables. It is likely in this

study that effects on one variable may be related to the effects on another variable.

Since the sample size of the present study was small, it was necessary to conduct a power analysis to ensure likelihood of obtaining true significant results. A power analysis for detecting effects of -1 standard deviation (SD) indicated an 80 per cent chance with a sample size of $N = 8$. This is considered a reasonable level of chance in this type of study. It is acknowledged, nevertheless, that the sample size is small.

Procedures and equipment The study was conducted at Charlotte Pass, Kosciuszko National Park, New South Wales. An intermediate level ski run accessed by a T-bar ski-lift was selected and used throughout the experiment. Waiting time in lift queues was minimal, ranging from zero to three minutes. This was an important consideration in ensuring that subjects did not cool down while waiting in lift queues. The study was conducted using full standardised ski equipment to replicate normal skiing conditions. The skiers were dressed in identical rental ski clothing during the warm-up and control conditions.

Baseline flexibility measures of the warm-up and control condition subjects were taken outside the base lodge. The warm-up condition subjects then moved to a flat area on the summit of the ski slope (at approximately 1900 metres elevation) where two sets of baseline measures of Tre, Tsk, and HR were recorded five minutes apart. The subjects then participated in the warm-up program. To ensure that subjects were not over-exerting themselves, measurements of HR and perceived exertion ratings (Borg 1971) were taken on three occasions during the warm-up. To complete the warm-up program, the subjects skied down to the base of the run, doing as many turns as was comfortable. Immediate post-warm-up measures (Tre, Tsk, HR and flexibility) were then taken from the warm-up subject(s).

Approximately 10 minutes after the second baseline measurement of the warm-up subject(s), two sets of control baseline (pre-skiing) measures of Tre, Tsk, and HR were then taken from the control condition subjects who had moved to the bottom of the ski run. These measures were taken five minutes apart. The time delay between the baseline measures of the

warm-up and control conditions was necessary due to the practical limitations of the study and the need to avoid having the subjects in the control condition standing out in the cold alpine environment. It was feared that this might alter the subjects' control condition Tre and therefore taint the results. The timing coincided as closely as possible with the warm-up subjects arriving at the base of the run following completion of the warm-up program. For comparison purposes, the baseline (pre-skiing) measures of the control condition were considered equivalent in time to the post-warm-up measures of the warm-up condition.

Flexibility measures were taken for both the warm-up and control condition subjects before the commencement of skiing and with the final set of measures at the end of 90 minutes of skiing.

The downhill skiing participated in by the subjects approximated normal skiing conditions within the constraints of taking the required measurements. Subjects were requested to allow at least one hour for rest prior to participation in a test session, to ensure accurate baseline measures.

Environmental considerations The strategy of warm-up condition subject(s) skiing at the same time as control condition subject(s) was used to minimise the effects of variations in environmental temperatures. Measurements of dry bulb air temperature and wind velocity were taken to monitor the environment at the time of testing, so that any varying effect that might influence the results could be determined, and in order to calculate the wind chill factor.

Results

There were no notable environmental differences between testing sessions. The following results are presented as mean (SD) values.

Warm-up condition One of the subjects fell during the first 15 minutes of skiing, without sustaining injury but dislodging the rectal probe. Therefore, Tre could only be analysed across seven subjects. Rectal temperature immediately following warm-up ($38.7 (0.5)$ degrees C) was significantly greater than Tre prior to warm-up ($38.0 (0.5)$ degrees C)

($F_{(1,6)} = 20.190, p < 0.001$), as was Tre after 30 minutes of skiing (38.9 (0.5) degrees C) ($F_{(1,6)} = 35.422, p < 0.001$), and Tre at 90 minutes skiing (38.6 (0.3) degrees C) ($F_{(1,6)} = 15.001, p = 0.001$).

Heart rate immediately post-warm-up (132 (23) b.min⁻¹) was significantly greater than pre-warm-up HR (97 (14) b.min⁻¹) ($F_{(1,7)} = 26.304, p < 0.001$), as was HR at 30 minutes of skiing (131 (23) b.min⁻¹) ($F_{(1,7)} = 23.927, p < 0.001$) and at 90 minutes of skiing (125 (17) b.min⁻¹) ($F_{(1,7)} = 16.271, p < 0.001$).

There were no significant effects for Tsk-thigh but Tsk-chest at 30 minutes of skiing (34.4 (1.1) degrees C) was significantly less than pre-warm-up measures (35.4 (1.1) degrees C) ($F_{(1,7)} = 5.336, p < 0.05$), as was Tsk-chest at 90 minutes of skiing (34.2 (1.7) degrees C) ($F_{(1,7)} = 7.192, p < 0.05$). At 30 minutes of skiing, Tsk-chest (34.4 (1.1) degrees C) was also significantly less than post-warm-up measures (35.4 (1.1) degrees C) ($F_{(1,7)} = 4.833, p < 0.05$), as it was at 90 minutes of skiing (34.2 (1.7) degrees C) ($F_{(1,7)} = 6.607, p < 0.05$).

The skin temperature of the calf at 30 minutes of skiing (31.5 (2.0) degrees C) was significantly less than pre-warm-up measures (33.5 (1.1) degrees C) ($F_{(1,7)} = 11.539, p = 0.0027$), as was Tsk-calf at 90 minutes of skiing (31.3 (2.0) degrees C) ($F_{(1,7)} = 13.672, p = 0.0013$). Tsk-calf at 30 minutes of skiing (31.5 (2.0) degrees C) was significantly less than post-warm-up measures (32.9 (1.4) degrees C) ($F_{(1,7)} = 5.309, p < 0.05$), as it was at 90 minutes of skiing (31.3 (2.0) degrees C) ($F_{(1,7)} = 6.785, p < 0.05$).

The sit-and-reach flexibility immediately post-warm-up (6 (8.5) cm) was significantly greater than pre-warm-up flexibility (11 (8.5) cm) ($F_{(1,7)} = 14.770, p = 0.0018$), as it was at 90 minutes of skiing (7 (8.5) cm) ($F_{(1,7)} = 9.569, p = 0.0079$).

Control condition Due to the omission of collecting one of the subject's flexibility data in the control condition at baseline, this variable could be analysed across only seven subjects. There were no significant effects for Tsk-thigh, Tsk-calf or flexibility.

Rectal temperature at 30 minutes of skiing (38.5 (0.6) degrees C) was significantly greater than the

baseline/pre-skiing value (37.9 (0.3) degrees C) ($F_{(1,7)} = 16.445, p = 0.0012$), as was Tre at 90 minutes of skiing (38.4 (0.3) degrees C) ($F_{(1,7)} = 11.916, p = 0.0039$).

Heart rate at 30 minutes of skiing (123 (17) b.min⁻¹) was significantly greater than the baseline/pre-skiing value (91 (11) b.min⁻¹) ($F_{(1,7)} = 30.752, p < 0.001$), as it was at 90 minutes of skiing (117 (17) b.min⁻¹) ($F_{(1,7)} = 19.955, p < 0.001$).

Skin temperature of the chest at 90 minutes of skiing (34.1 (0.8) degrees C) was significantly less than the baseline/pre-skiing value (35.0 (1.1) degrees C) ($F_{(1,7)} = 9.308, p = 0.0086$). Skin temperature of the chest at 90 minutes of skiing (34.1 (0.8) degrees C) was significantly less than 30 minutes of skiing (35.0 (0.8) degrees C) ($F_{(1,7)} = 8.456, p = 0.0115$).

Warm-up versus control conditions Warm-up condition baseline values of Tre were not significantly different from the control condition baseline/pre-skiing values (Figure 1). Rectal temperature immediately post-warm-up (38.7 (0.5) degrees C) was significantly greater than the control baseline/pre-skiing Tre (37.9 (0.3) degrees C) ($F_{(1,6)} = 26.160, p < 0.001$). Rectal temperature of the warm-up condition at 30 minutes skiing (38.9 (0.5) degrees C) was significantly greater than control condition values (38.5 (0.5) degrees C) ($F_{(1,6)} = 8.196, p = 0.0076$). There were no significant effects for Tsk.

Warm-up condition baseline values of HR were not significantly different from the control condition baseline/pre-skiing values (Figure 2). Immediately post-warm-up HR (132 (23) b.min⁻¹) was significantly greater than control baseline/pre-skiing values (91 (11) b.min⁻¹) ($F_{(1,7)} = 32.972, p < 0.001$). There were no significant differences detected between the two conditions at 30 minutes or 90 minutes of skiing.

There was no significant difference between sit-and-reach flexibility of the warm-up and control conditions at baseline/pre-skiing. Sit-and-reach flexibility immediately post-warm-up (5 (8) cm) was significantly greater than baseline/pre-skiing control flexibility (9 (8) cm) ($F_{(1,6)} = 10.145, p = 0.0034$).

Perusal of the graphical representation of the results

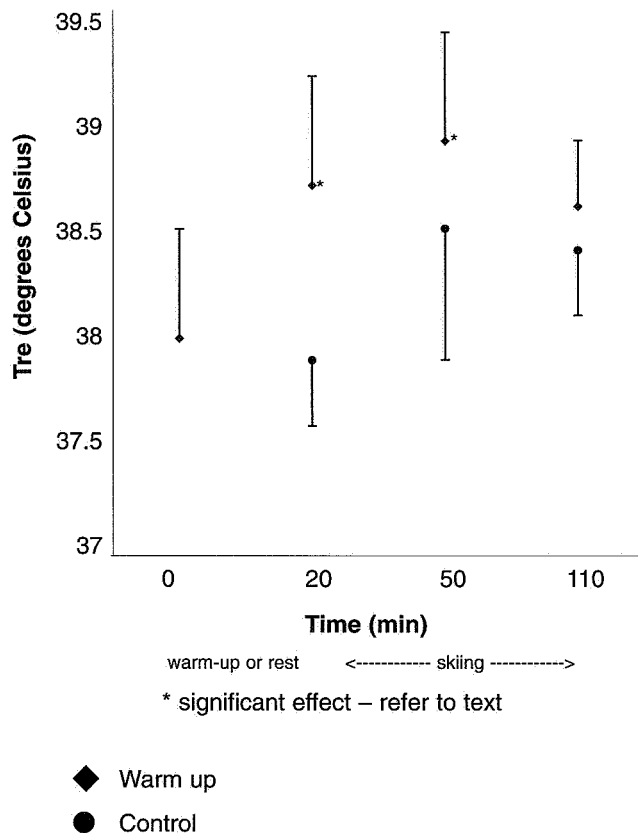


Figure 1. Rectal temperature (Tre) during downhill skiing.

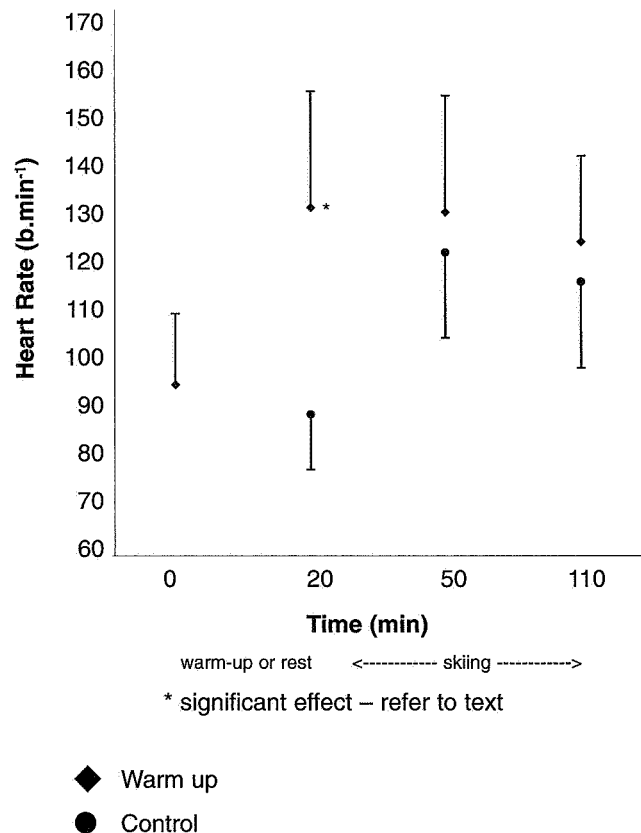


Figure 2. Heart rate during downhill skiing.

suggested that the effect of warm-up on Tre may have lasted for only 45 minutes, and on HR for 15 minutes. Therefore, a post-hoc repeated measures ANOVA was performed on Tre at 45 minutes of skiing and on HR data at 15 minutes of skiing to determine where the significant differences ceased between the conditions on these two variables. Neither of these comparisons exhibited significant differences, supporting the idea that the effect of warm-up had dissipated.

Discussion

The purpose of this study was to determine whether the on-snow warm-up program did effectively “warm

up” the body. Analyses reported in the warm-up condition indicated that the warm-up program did in fact warm up the participants. This was reflected by the significant increases in Tre, HR and flexibility. The results of the control condition indicated that skiing without warm-up also significantly elevated Tre and HR.

The findings that Tre for the warm-up and control conditions were not significantly different at baseline makes other comparisons meaningful as they will not be due to initial differences. We can therefore be more confident that differences at 30 and 90 minutes of skiing are related to the warm-up intervention. Rectal temperature for the warm-up condition was significantly higher than the control condition at the immediate post warm-up/pre-skiing measurement

and at 30 minutes of skiing, providing evidence for the effectiveness of the warm-up program. These results support the findings of Robergs et al (1991) who reported a significant increase in Tre with stationary cycling warm-up when compared with a no warm-up trial. The significant difference was lost by 45 minutes of skiing in the present study, as the warm-up condition temperature gradually declined and the control condition temperature gradually increased. There was a plateau effect for both conditions between 45 and 90 minutes of skiing. However, the control condition never attained values as high as the warm-up condition. Therefore, participation in the warm-up program provided at least a 30min (up to 45min) advantage in terms of elevating Tre when compared with no warm-up.

The findings that HR for the warm-up and control conditions were not significantly different at baseline, but that HR for the warm-up condition was significantly higher than the control condition at the immediate post warm-up/pre-skiing measurement, provide further evidence for the effectiveness of the warm-up program. These findings support that of De Bruyn-Prevost (1980) who reported significantly higher HR values following stationary cycling warm-up as compared with no warm-up trials. The control condition in the current study never attained values as high as the warm-up condition, which is an indication that cardiovascular function was not increased to the same extent as in the warm-up condition. This implies that participation in the warm-up program increased cardiovascular function when compared with the control condition for up to the first 15 minutes of skiing.

The significant increases in Tre and HR following 30 minutes of skiing in the control condition, which were maintained for 90 minutes of skiing, provide evidence that the exercise of skiing itself does elevate Tre and HR.

There were no significant differences detected in Tsk between the two conditions, with both exhibiting general trends of gradual decline, indicating that both conditions had similar responses to the cold alpine environment. This finding may be related to that of Chwalbinska-Moneta and Hanninen (1989) who studied the effect of warm-up compared with no warm-up prior to stationary cycling until exhaustion in an ambient temperature of 25 degrees C. They reported that, for the warm-up group, Tsk values did

not increase significantly during exercise as they did for the no warm-up group. Further, they found a significant fall in mean Tsk during the recovery period. Also of relevance is the finding of Hurley and Haymes (1982) who studied the effects of subjects sitting in a neutral environment (25 degrees C) for 30 minutes before cycling for 60 minutes in 10 degrees C. They reported a significant decrease in Tsk.

Following participation in the warm-up program, the subjects' flexibility improved and was significantly better than that of the control condition subjects. This improvement in flexibility is likely to be a result of the stretches and exercises included in the warm-up program as well as the increases in deep body temperature and the assumed increases in muscle temperature. This difference was not maintained at 90 minutes of skiing. For skiing, stretching is considered important to ensure adequate joint movement that may occur during falls (Morrissey et al 1987). Stretching is also advocated to improve physical performance (Ciullo and Zarins 1983, Shellock and Prentice 1985). Wilson et al (1991) in their study on the relationship between stiffness of musculature and static flexibility, suggest that a more compliant system will be able to absorb forces over a greater time period and distance as compared with a stiff system.

Whether the relatively short-term advantages of the warm-up program are beneficial in terms of improved performance and injury prevention, and whether it is necessary to repeat the program periodically throughout the day, requires further research.

Limitations Gentle skiing was used to complete the warm-up program as a precursor to free skiing. Its inclusion does, however, raise the possibility of the skier injuring themselves during this part of the program, and the inevitable variations in the subjects' skiing techniques may affect the data.

The warm-up program was designed to include all the body parts relevant for skiing in the exercises and stretches, and to increase deep body temperature in the cold alpine environment through a combination of length and intensity of the program. However, it is acknowledged that the program is likely to be too long, and the exercises possibly too difficult, for the average recreational skier. Further research could examine the effectiveness of a shorter, less difficult program.

Field investigations, by their nature, are difficult to control, although much care was taken in design and methodology. The method of the sit-and-reach flexibility test used is acknowledged as a limitation. Measurement error, intra-rater reliability, and test-retest reliability were not calculated for this test by the authors. In order to address these issues in future research it is recommended that the test be more standardised, perhaps by using a rigid board that could be transported to the snowfield. The subject's knees could be held in extension by straps on the board, and ideally the investigators performing the measurements would be blinded to the readings. If these limitations are addressed, the authors would be more confident that the changes in flexibility found in this study were in fact real changes.

Conclusions

When the warm-up and control conditions were compared, participation in the warm-up program did provide an advantage of up to 30-45 minutes with respect to elevating Tre. Heart rate in the warm-up condition was increased for up to the first 15 minutes of skiing when compared with the control condition. For the measures of Tre and HR, the control condition never attained values as high as those for the warm-up condition. Flexibility improved significantly following participation in the warm-up program. The measures of flexibility for the control condition were never as low (ie more flexible) as those of the warm-up condition.

Recommendations This study has demonstrated greater increases in Tre, HR, and flexibility following participation in the warm-up program when compared with a control condition. The literature supports participation in a warm-up program prior to participation in sport, in order to raise Tre and HR, and improve flexibility. It is considered important that the main components of general exercise, context specific exercise, and flexibility exercises are included in such warm-up programs.

Future directions Further research suggested by this investigation could pursue the question "Is a combination of stretches and gentle skiing an adequate warm-up?" Research into the relationship between warming up and the improvement of physical performance and risk of injury is warranted.

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References

- Anderson B and Burke ER (1991): Scientific, medical and practical aspects of stretching. *Clinics in Sports Medicine* 10: 63-86.
- Astrand P-O and Rodahl K (1986): Textbook of Work Physiology - Physiological Bases of Exercise. (3rd ed.) New York: McGraw-Hill Book Company.
- Bixler B and Jones R.L (1992): High-school football injuries: effects of a post-halftime warm-up and stretching routine. *Family Practice Research Journal* 12: 131-139.
- Borg G (1971): The perception of physical performance. In Shephard RJ (Ed.): *Frontiers of Fitness*. Springfield: Charles C Thomas, pp. 280-294.
- Chwalbinska-Moneta J and Hanninen O (1989): Effect of active warming-up on thermoregulatory, circulatory, and metabolic responses to incremental exercise in endurance - trained athletes. *International Journal of Sports Medicine* 10: 25-29.
- Ciullo JV and Zarins B (1983): Biomechanics of the musculotendinous unit: relation to athletic performance and injury. *Clinics in Sports Medicine* 2: 71-86.

- De Bruyn-Prevost P (1980): The effects of various warming up intensities and durations upon some physiological variables during and exercise corresponding to the WC170. *European Journal of Applied Physiology* 43: 93-100.
- Gillette TM, Holland GJ, Vincent WJ and Loy SF (1991): Relationship of body core temperature and warm-up to knee range of motion. *Journal of Orthopaedic and Sports Physical Therapy* 13: 126-131.
- Harris ML (1969): Flexibility - review of the literature. *Physical Therapy* 49: 591-601.
- Hays W (1988): Statistics. (4th ed.) London: Holt, Rinehart and Winston.
- Hoeger WWK and Hopkins DR (1992): A comparison of the sit and reach and the modified sit and reach in the measurement of flexibility in women. *Research Quarterly for Exercise and Sport* 63: 191-195.
- Hurley BF and Haymes EM (1982): The effects of rest and exercise in the cold on substrate mobilization and utilization. *Aviation, Space, and Environmental Medicine* 53: 1193-1197.
- Jendrusch G, Richter F and de Marees H (1994): Dynamic visual acuity before and after treadmill ergometry. *International Journal of Sports Medicine* 15: 346.
- Kapandji IA (1974): The Physiology of the Joints. Volume Three - The Trunk and the Vertebral Column. (2nd ed.) Edinburgh: Churchill Livingstone.
- Madding SW, Wong JG, Hallum A and Medeiros JM (1987): Effect of duration of passive stretch on hip abduction range of motion. *Journal of Orthopaedic and Sports Physical Therapy* 8: 409-416.
- Matyas TA and Bach TM (1985): The reliability of selected techniques in clinical arthrometrics. *Australian Journal of Physiotherapy* 31: 175-199.
- Morrissey MC, Seto JL, Brewster CE and Kerlan RK (1987): Conditioning for skiing and ski injury prevention. *Journal of Orthopaedic and Sports Physical Therapy* 8: 428-437.
- O'Brien B, Payne W, Gastin P and Burge C (1997): A comparison of active and passive warm ups on energy system contribution and performance in moderate heat. *Australian Journal of Science and Medicine in Sport* 29: 106-109.
- Raas E (1987): The International Ski Federation contribution to safety in skiing. In Mote CD and Johnson RJ (Eds): Proceedings of Skiing Trauma and Safety Sixth International Symposium. Philadelphia: American Society for Testing and Materials STP 938, pp. 329-332.
- Robergs RA, Pascoe DD, Costill DL, Fink WJ, Chwalbinska-Moneta J, Davis JA and Hickner R (1991): Effects of warm-up on muscle glycogenolysis during intense exercise. *Medicine and Science in Sports and Exercise* 23: 37-43.
- Rosenbaum D and Hennig EW (1995): The influence of stretching and warm-up exercises on Achilles tendon reflex activity. *Journal of Sports Sciences* 13: 481-490.
- Safran MR, Garrett WE, Seaber AV, Glisson RR and Ribbeck BM (1988): The role of warm-up in muscular injury prevention. *American Journal of Sports Medicine* 16: 123-129.
- Sapega AA, Quedenfeld TC, Moyer RA and Butler RA (1981): Biophysical factors in range-of-motion exercise. *The Physician and Sportsmedicine*. 9: 57-65.
- Shellock FG and Prentice WE (1985): Warming-up and stretching for improved physical performance and prevention of sports-related injuries. *Sports Medicine* 2: 267-278.
- Taylor DC, Dalton JD, Seaber AV and Garrett WE (1990): Viscoelastic properties of the muscle-tendon units - the biomechanical effects of stretching. *American Journal of Sports Medicine* 18: 300-309.
- Whelan K (1996): Downhill skiing injuries: associated factors and prevention strategies. *Physical Therapy Reviews* 1: 105-110.
- Williams J, Grimmer KA and Holland L (1996): Incidence of injury in metropolitan touch players. Proceedings of the Australian Conference of Science and Medicine in Sport. Canberra, pp. 364-365.
- Williford HN, East JB, Smith FH and Burry LA (1986): Evaluation of warm-up for improvement in flexibility. *American Journal of Sports Medicine* 14: 316-319.
- Wilson GJ, Wood GA and Elliott BC (1991): The relationship between stiffness of the musculature and static flexibility: an alternative explanation for the occurrence of muscular injury. *International Journal of Sports Medicine* 12: 403-407.

Appendix 1 Warm-up exercises presented in the order undertaken.

Sliding skis back and forward on the spot 1.5 minutes

Hamstrings stretch

With the ski poles placed out to the sides for support, place the tail of one ski in the snow out in front so that the ski is pointing vertically. Straighten the knee until a stretch is felt in the back of the thigh . or behind the knee (20 seconds x 4)

Side stepping

Step sideways with the right foot and then bring the left foot over to meet it. Then step back to the original position with the left foot and bring the right foot back to meet it. This exercise may be progressed by adding a slight hop. 1.5 minutes

Adductor stretch

With skis wide apart, bend one knee while keeping the other knee straight. You should feel a stretch on the inside of the straight leg. Repeat to the other side (Gamma 1981). (20 seconds x 4)

Half squats with spinal and arm flexion /extension

While holding the poles, bend the knees down into a squatting position at the same time as taking the arms down and backwards. Then stand up straight again whilst raising the arms overhead (Victorian Alpine Safety Committee, 1992). 1.5 minutes

Quadriceps stretch

Leaning on one pole out to the side, bend the opposite leg behind so that the tip of the ski is in the snow. Pull the tail of the ski towards the shoulder with the free hand until a stretch is felt in the front of the thigh. (20 seconds x 4)

Flexion twists

With skis wide apart and knees bent, reach one hand down to the outside of the opposite boot and reach backwards with the other arm. Repeat to the other side (Australian Physiotherapy Association 1991, Gamma 1981, Victorian Alpine Safety Committee, 1992). 1.5 minutes

Spinal stretches

Lateral flexion: With poles clasped together overhead and skis apart, bend from side to side (Gamma 1981, Victorian Alpine Safety Committee, 1992). (5 seconds/5 seconds x 2)

Flexion/extension: Without the poles and with the legs straight, bend down slowly towards your ankles. After straightening up, place your hands in the small of your back and arch backward as far as is comfortable. (5 seconds/5 seconds x 2)

Rotation: Standing with skis apart, twist around to one side as far as is comfortable to plant pole behind. Repeat to the other side (Victorian Alpine Safety Committee, 1992). (5 seconds/5 seconds x 2)

Knee lifts with arm swings

While holding the poles, bend one knee and lift it forwards whilst raising the opposite arm. Repeat to the other side. 1.5 minutes

Calf stretch

Slide one ski in front of the other. Bend the front knee but keep the back knee straight. Lean forward resting on the poles until a stretch is felt in the calf of the back leg (Victorian Alpine Safety Committee, 1992). (20 seconds x 4)

Side-to-side hip swivels

With skis parallel plant the right pole while moving the pelvis to the left. Then raise the right pole, plant the left pole and move the pelvis to the right. Repeat. 1.5 minutes

Skiing down a gentle slope doing as many turns as is comfortable