1991

Determinants Of Critical Power And Anaerobic Work Capacity In Young And Elderly Men

Thomas James Overend

Recommended Citation

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DETERMINANTS OF CRITICAL POWER AND ANAEROBIC WORK CAPACITY IN YOUNG AND ELDERLY MEN

by

Thomas James Overend

Faculty of Kinesiology

Submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Graduate Studies
The University of Western Ontario
London, Ontario
October 1991

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ABSTRACT

Determinants of critical power (CP, the theoretical maximal rate of non-fatiguing work) and anaerobic work capacity (AWC, a finite energetic reserve from intra-muscular sources) were determined in young (n=13, 24.5 y) and elderly men (n=12, 70.7 y). The purposes of the four studies were to: 1a) determine and compare CP and AWC in young and elderly men; 1b) determine if CP does represent a true maximal rate of non-fatiguing work; 2) determine thigh component cross-sectional areas (CSA) and volumes; 3) determine the strength and strength/CSA ratios of the knee extensors and knee flexors; and 4) identify determinants of CP and AWC.

The first study showed that CP (115 vs 177 watts) and AWC (8.1 vs 13.6 kJ) were significantly reduced in elderly men. Temporal profiles of cardiorespiratory and metabolic variables monitored during prolonged (24 minutes) cycle exercise at CP indicated that CP elicited a significantly greater $\dot{V}O_2$ in the elderly men (91.5% vs 85.2% of $\dot{V}O_2$max) and that CP did not represent a true rate of non-fatiguing work in either young or elderly men.

The computed tomography scans used in the second study indicated that subcutaneous and intramuscular fat in the thigh were significantly increased in the elderly men, while the quadriceps and hamstring muscle CSA and volumes were decreased in comparison to the young men.

The third study showed that elderly men were weaker (22-32%) in both concentric isometric and isokinetic (120°/s) knee flexion and extension. Isometric strength:CSA ratios were not different between the two groups, but the isokinetic ratios of the elderly men were significantly decreased, suggesting that their decline in isokinetic strength was greater than could be accounted for by their decrease in muscle CSA.

Finally, the fourth study indicated that while CP was correlated with measures of muscle CSA and volume, it was most strongly related to $\dot{V}O_2$max and maximal power output in both young and elderly men.

These studies have identified determinants of CP and AWC and suggest a possible age-related effect on muscle strength and size, but not on the ability of elderly men to perform high intensity exercise for prolonged durations.

ACKNOWLEDGEMENTS

I would like to acknowledge the contributions of the many people who have helped bring this dissertation to fruition. My advisor, Dr. David Cunningham, provided timely advice and encouragement throughout my years of doctoral education. The members of my advisory and examining committees, Drs. John Kowalchuk, John Kramer, Michelle Mottola, Don Paterson, Bert Taylor, Scott Thomas and Tony Vandervoort kept me on track and offered constructive criticism. I must also thank the young and elderly men who served as subjects in my studies, for their involvement, enthusiasm and significant time commitment.

I would like to thank Joan Macrow, the Graduate Program secretary, Jean Neal, secretary to the Dean, and Dr. George Wearring, professor of life, for all their help, friendship and caring concern over the years. I will remember them all with fondness.

My primary research was carried out using the facilities and equipment at the Centre for Activity and Ageing. I would like to thank the Director, Dr. Peter Rechnitzer, and the staff at the Centre, Nancy Ecclestone, Brad Hansen, Marian Henderson, Barbara Kaluzny, Elizabeth Nowicki, and Don Smith for their support and assistance in all matters technical and administrative.

I am also grateful to Dr. Robert Klein of the Department of Physiology for the use of his flame photometer for the

potassium assays, and to Dr. Michael Lefcoe and Pat Markvoort of Victoria Hospital for their assistance with the computed tomography scans.

The Ontario Ministry of Health's Research Personnel Development Program provided personal financial support during much of my graduate career. I would like to thank the Ministry for enabling me to focus on academic rather than financial concerns over the past years.

Perhaps the best part of graduate study is the friendship one develops with other students who are there when needed to challenge, to support, to inspire, to commiserate with and to congratulate. In particular, I would like to thank Tim Doherty, Greg Marsh, Javier Padilla, Michelle Porter, Marc Poulin, Charles Rice, Claudette St. Croix and Sue van Evra, and I wish them all the best in their future endeavours along our common path.

I would like to thank my parents and family for their consistent understanding, support and encouragement of their "perpetual student". You always seemed to know that I would finish, even when I was doubtful, and that helped. Finally, and most of all, I want to say a heartfelt thanks to Lisa, who was there at the beginning and at the end, providing love and friendship throughout.

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CHAPTER ONE

GENERAL INTRODUCTION AND BACKGROUND

1.1 Critical Power and Anaerobic Work Capacity

In 1965, French researchers Hugues Monod and Jean Scherrer published a paper introducing two measures of physical performance. Monod and Scherrer discovered that a certain maximal amount of work could be performed by a muscle or muscle group at any given power output before the onset of local exhaustion, defined as the time when the muscle or muscle group could no longer maintain the imposed power output. This amount of work could be calculated by multiplying the power output by the time to fatigue at that power output.

Monod and Scherrer termed the amount of work performed during a dynamic task until exhaustion, "work limit" (W_{lim}), and the time to fatigue, "time limit" (t_{lim}). They also discovered that a strong linear relationship existed between W_{lim} and t_{lim} when data from several different power outputs were plotted (Fig. 1). This linear relationship was given by the equation $W_{lim} = a + b(t_{lim})$. Monod and Scherrer termed the slope parameter (b), the rate of energy reconstitution of the muscle or muscle group, or "critical power" (CP), and defined this as the maximal power output that could be maintained for a very long time without fatigue. The y-intercept (a) was defined as an energetic reserve utilized by the muscle at work rates

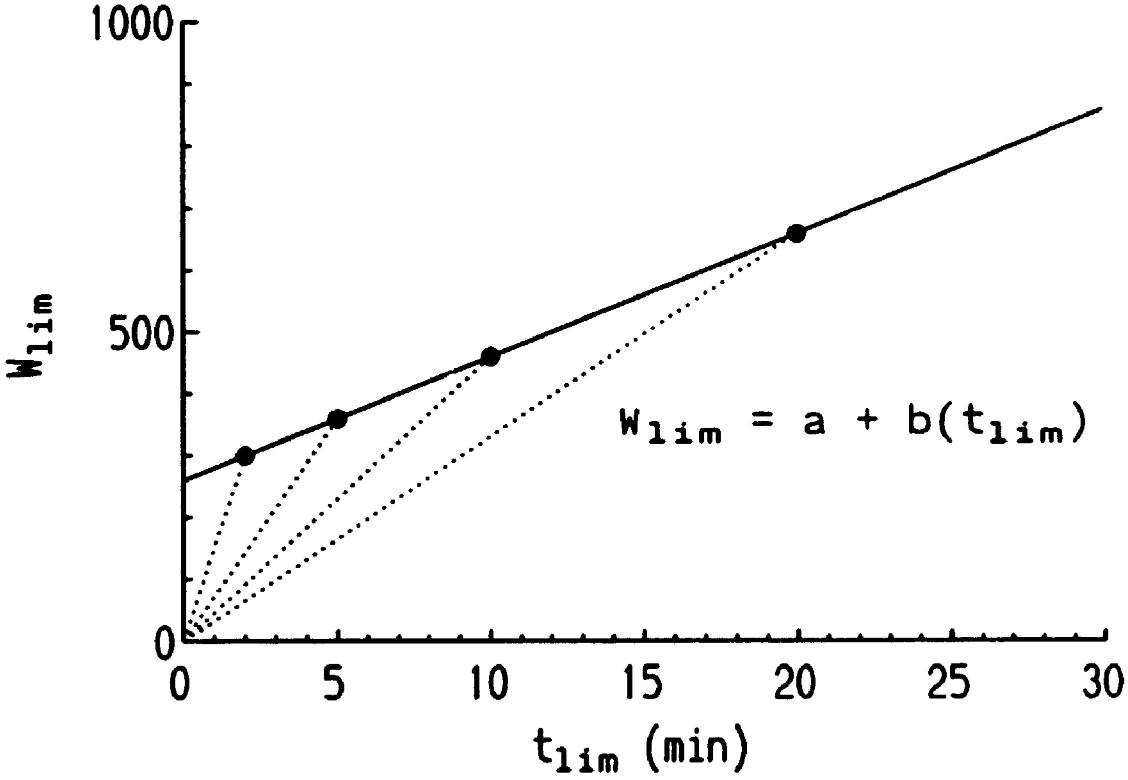


Fig. 1 Determination of energy reconstitution rate and anaerobic reserve from four tests to fatigue at different power outputs (from Monod and Scherrer, 1965).

greater than critical power. Thus, the maximal amount of work that a muscle or muscle group is capable of at any given power output is determined as the sum of the rate of reconstitution of energy from aerobic sources plus an energetic reserve from anaerobic sources. The studies of Monod and Scherrer showed that each muscle or muscle group had distinct values for both the energetic reserve and the rate of reconstitution of energy. Monod and Scherrer also showed that the energy reconstitution rate is linked to circulatory conditions in the muscle. By occluding blood flow in the exercising muscle, they found that W_{lim} was determined only by the size of the energetic reserve.

Moritani et al. (1981) applied the concepts of Monod and Scherrer to exercise on cycle ergometers. They found that the linear relationship between W_{lim} and t_{lim} also existed for whole body exercise. Moritani et al. reported that CP was significantly related to both maximal oxygen consumption ($\dot{V}O_2max$) and the anaerobic threshold (measured as the ventilation threshold, $\dot{V}eT$), and using hypoxic protocols, confirmed that CP was dependent on the level of oxygen in the blood while the energetic reserve was not. Bulbulian et al. (1986) introduced the term "anaerobic work capacity" (AWC) to refer to the energetic reserve, and the nomenclature, CP and AWC, will be used throughout the balance of this thesis.

Whipp et al. (1982) described a slightly different technique for determining variables analogous to CP and AWC.

Briefly, Whipp et al. linearized the inverse hyperbolic relationship between power output (P) and time (t) by plotting P vs the inverse of time (1/t). They derived a fatigue threshold (θ_f) and work constant (W') from the equation ($P = W'/t + \theta_f$). An example of the derivation of θ_f and W' by the technique of Whipp et al. is given in Appendix II.

Since the work of Moritani et al. (1981), there has been an increased interest in the concepts of CP and AWC. CP and AWC were confirmed for treadmill exercise (Hughson et al., 1984), and a comprehensive investigation of the metabolic and respiratory factors associated with prolonged exercise at CP and at CP+5% was carried out by Poole et al. (1988). They showed that while $\dot{V}O_2$ reached a plateau during exercise at CP, it continued to rise during exercise at CP+5%, as did blood lactate and ventilation, suggesting that CP may indicate some type of non-fatiguing work rate.

Gaesser and Wilson (1988) studied responses of CP and AWC to aerobic interval and continuous training and showed that both types of training resulted in increases in CP while AWC was unchanged. This finding was later confirmed by Poole et al. (1990). Nebelsick-Gullett et al. (1988) investigated the nature of AWC and reported that it was significantly related to anaerobic capacity determined from the benchmark Wingate cycle ergometer test. Other researchers (Housh et al., 1988; Scarborough et al., 1991) investigated the concept that CP represented the maximal rate of non-fatiguing work, an attractive theory for predicting endurance performance.

Despite the recent interest in CP and AWC, little work has been directed towards identifying determinants of these variables. The early investigations of Monod and Scherrer (1965) and Moritani et al. (1981) established that CP and AWC reflected the aerobic and anaerobic energy systems, respectively. Thus, CP should be related to variables measuring cardiorespiratory performance, while AWC should be linked to variables associated with strength and power. Identification of determinants of CP and AWC should aid in developing a better understanding of their physiological and functional significance. The first general purpose of this dissertation was to investigate relationships between CP and AWC, and measures of aerobic power, muscle cross-sectional area, muscle volume and muscle strength.

1.2 Critical Power, Anaerobic Work Capacity, and Ageing

The second purpose of this thesis was to investigate CP and AWC in an elderly group of subjects since all previous work with these variables has been carried out on young adults. One might expect CP and AWC to be influenced by age since ageing is associated with marked decreases in many physiological functions. If CP represents the maximal rate of non-fatiguing work, AWC the maximal anaerobic work capacity, and jointly they determine the maximal amount of work performed at any given power output, it would be of interest to ascertain the extent by which this rate and capacity may be altered by age.

Conclusive determination of the effect of ageing on any variable of interest however, is complicated by several factors. The first has to do with study design. Convenience usually dictates that research pertaining to ageing primarily uses cross-sectional (comparing subjects of different ages) rather than longitudinal (following the same subjects throughout the ageing period) designs Cross-sectional designs tend to over-emphasize age differences while longitudinal designs tend to under-estimate these differences. The main disadvantage of cross-sectional designs is that they can never be used to evaluate age changes in single individuals since it is very difficult to get subjects in different groups matched in all respects except age. Despite this source of bias however, an estimate of average age trends can be made and variables showing age-related trends can be identified for further study by longitudinal design.

A second complication of research on ageing, and one of particular relevance to studies involving exercise, is that of subject selection. Subjects volunteering for exercise studies probably do not represent the average or normal ageing population, thus generalizing results from these subjects to the larger population can only be done with reduced confidence. A totally random subject selection may resolve this problem, but only if all subjects are able to manage the physical demands of the exercise in question. For maximal exercise, infirm or otherwise incapable subjects are usually weeded out in pre-test screening, thus resulting in the same problem with generalizing results.

A central question in ageing is whether loss of function over time reflects a true loss due to ageing per se (primary ageing), or whether the loss is partially or even completely due to inactivity, disability or disease (secondary ageing). A recent theory in ageing research suggests that the true effects of ageing can best be determined by studying the "successful" type of ageing, instead of the "usual" type which is associated with the above age-related problems (Rowe and Kahn, 1987). In this respect, Calne et al. (1991) have defended the need to study both normal (usual) and super-normal (successful) types when investigating ageing of the nervous system. Elderly subjects accepted into exercise studies could be characterized as having successfully aged for the ability to perform vigourous exercise, since normal exclusion procedures screen out any subjects with limiting respiratory, cardiovascular or musculoskeletal conditions. Therefore, within the limitations of design and subject selection, cross-sectional studies of active, healthy, elderly men such as those used in this dissertation, can still yield information of value in determining the effects of ageing on exercise performance.

1.3 Thesis Outline

The balance of this thesis consists of four chapters, each organized as a research study including an Introduction with literature review, Methods, Results and Discussion. References have been grouped at the end of the thesis, and attempts have been made to limit explanation of methods common to more than one study. In the first study (Chapter Two), CP and AWC were determined and compared in young and elderly men, and then the physiological responses to prolonged work at CP were examined to determine if CP does represent the maximal rate of non-fatiguing work.

Chapters Three and Four investigated possible determinants of CP and AWC. In Chapter Three, a multiple slice, computed tomography scan technique was used to accurately determine cross-sectional areas and volumes of the quadriceps and hamstring muscles of young and elderly men. In Chapter Four, the isokinetic and isometric strength of the knee extensors and knee flexors were determined. This permitted a comparison of the strength:cross-sectional area ratios between young and elderly men.

Chapter Five was a correlative study intended to identify determinants of CP and AWC from the variables measured in Chapters Two through Four. Multiple regression was used in an attempt to predict CP and AWC from significant correlates. A general conclusion in Chapter Six summarizes the findings from the four studies, and presents some ideas for future research direction.

1.4 Subject Selection

In order to prevent repetition throughout the four studies, a description of the subject selection process is given here. Young (20-35 yrs, n=13) and elderly (65 yrs+, n=13) active men responding to advertisements were recruited into the study. "Active" was defined as involvement in physical activities at recreational or participative levels, but excluding those in training for competitive sport. Elderly subjects underwent a pre-study medical exam and maximal exercise stress test to eliminate those with any limiting cardiovascular, respiratory or musculoskeletal problems. One elderly subject was rejected after a positive sign for cardiovascular disease was detected during the stress test. This paragraph detailing subject selection procedures will be referred to in each of the next four chapters.

All procedures for the study were approved by The University of Western Ontario's Review Board for Health Science Research Involving Human Subjects, and all subjects provided their informed consent. The subjects took part in all procedures outlined in the Methods sections of Chapters Two, Three, Four and Five. This required a total of seven testing days. Five visits were made to the cardiorespiratory lab (two sessions for the determination of $\dot{V}O_2$max, two sessions for determination of CP and AWC, and a final session for the extended duration ride at CP). Single sessions were required for each of the CT and strength testing procedures. Details of the procedures used in each study are given in the respective Methods sections.

CHAPTER TWO

PROLONGED EXERCISE AT CRITICAL POWER IN YOUNG AND ELDERLY MEN

2.1 INTRODUCTION

The critical power of a muscle (Monod and Scherrer, 1965) may be calculated by determining endurance time (t_{lim}) at several different power outputs (p), then plotting total work performed by that muscle at each power output [W_{lim} (= p x t_{lim})] against t_{lim} and deriving an equation from the linear relationship [$W_{lim} = a + b(t_{lim})$] (Fig. 1, p.2). The slope coefficient (b) has been termed critical power (CP) and is thought to represent the maximal rate of non-fatiguing work of a muscle. The y-intercept (a) has been termed anaerobic work capacity (AWC) and may represent a finite store of intramuscular energy available to the muscle at work rates greater than CP. The CP concept has recently been extended to whole body exercise on cycle ergometers (Moritani et al., 1981) and treadmills (Hughson et al., 1984).

The question of whether CP represents a maximal rate of non-fatiguing work has been investigated in young men. Poole et al. (1988) found that fatigue occurred in approximately 18 minutes at a power output of CP+5%. Housh et al. (1989) showed that exercise at CP could only be maintained for approximately 33 minutes, while at CP+20%, the duration fell to around 8 minutes.

It is well established that ageing results in decreases in aerobic power (Buskirk and Hodgson, 1987; Rogers et al., 1990). In addition, it has been established that knee extensor strength (Young et al., 1985), quadriceps size (Klitgaard et al., 1990) and knee extensor endurance (Nakao et al., 1989) decline with age, while Makrides et al. (1985) have described further age-related losses in anaerobic power and capacity.

Critical power and AWC have not previously been determined in the elderly. The protocol for determination of CP and AWC is rigorous, involving three to five exhaustive exercise bouts at varying power outputs. Given that CP and AWC may represent functionally significant indicators of exercise capacity, the first purpose of this study was to determine if these variables can be determined in the elderly and to compare such findings with those from younger subjects. The second purpose was to evaluate the hypothesis that CP represents the maximal rate of non-fatiguing work.

2.2 METHODS

2.2.1 Test Protocols

All tests were performed in an air conditioned laboratory (range 20-23°C). Subject selection procedures were as described in Chapter One (p.9). Subjects were requested not to eat or to drink coffee within two hours prior to any test. An electrically braked cycle ergometer (Lode) equipped with toe clips and adjusted for seat height was used for all testing. Each test was preceded by a standard four minute unloaded warmup at 60 rev·min^{-1}. A revolution indicator mounted on the bike provided feedback. During each test, inspired and expired ventilation flow rates were measured using a bi-directional turbine (Alpha Technologies, VMM 110) calibrated daily with a syringe of known volume (3.01 l). Inspired and expired gases were sampled continuously (1 ml·sec^{-1}) at the mouth and analyzed by a mass spectrometer (Perkin-Elmer MGA-1100) calibrated daily with precision-analyzed gas mixtures. Analog signals were sampled and digitized every 10 milliseconds. Changes in gas concentration signals were aligned with the inspired and expired volumes by measuring the time delays for a square wave of gas passing the turbine to a resulting change in gas concentration. Breath-by-breath determination of expired ventilation ($\dot{V}E$), oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER), and end-tidal O_2 and CO_2 pressures ($PetO_2$ and $PetCO_2$) was performed using the algorithms of Beaver et al. (1981). A filter was used to remove breaths deviating from a five breath moving average by more than 20%. Heart rates (HR) were monitored via ECG recordings.

2.2.2 Determination of Maximal Oxygen Uptake

Subjects performed two ramp function tests (Whipp et al., 1981) to fatigue for determination of maximal $\dot{V}O_2$, $\dot{V}E$, HR, RER and power output (P_{max}). The ramp slopes were chosen to elicit fatigue in approximately eight to 12 minutes. Ramp tests were separated by at least one day. The reliability of a ramp test has been previously established (Whipp et al., 1981). Data from the test eliciting the highest $\dot{V}O_2$ were assumed to represent maximal values for the variables under study.

2.2.3 Determination of Critical Power

Time to fatigue was determined from each of four constant load tests to fatigue. Power outputs for the tests were chosen to elicit fatigue over the approximate range of two to 15 minutes. Pilot testing (n=2) had indicated that work rates between 65 and 95% of P_{max} would produce the desired range of times to fatigue. Two tests were performed on each testing day with a minimum 40 minute rest between tests and at least one day between testing sessions. The initial power output on each testing day was randomly selected and the second was chosen to ensure that subjects did not perform either the two longest or two shortest tests on a given day. Time to fatigue was measured from the onset of work rate to the second time that the subject failed to maintain a pedalling rate of 60 $rev \cdot min^{-1}$. Subjects were free to choose their own pedalling rate and received verbal encouragement throughout the test. The reliability of time to fatigue in such constant load tests has been previously established (Poole et al., 1988).

In the interest of precision, the original terms used by Monod and Scherrer (1965) to denote work (W_{lim}) and time (t_{lim}) were termed Wk_{tot} and t_f, respectively, in the present study. Time to fatigue (t_f) for each test was multiplied by the power output (p) to give total work performed (Wk_{tot}). Wk_{tot} for each test was then plotted against t_f for each test to give the linear relationship $Wk_{tot} = a+b(t_f)$ (Monod and Scherrer, 1965, Overend et al., 1991) (Fig. 2). Linear regression techniques were used to derive CP (slope coefficient, b) and AWC (y-intercept, a) from the plots of Wk_{tot} vs t_f. The values for AWC in watt·minutes were multiplied by 60 to convert to joules and then expressed in kilojoules.

2.2.4 Criterion Duration Test

To examine the hypothesis that CP represents the maximal rate of non-fatiguing work, all subjects attempted to complete a 24 minute ride at a power output corresponding to their CP. The 24 minute duration was selected to permit comparison with previous research (Poole et al., 1988). Subjects received verbal encouragement throughout the test period.

Gas exchange was monitored continuously. Data were averaged over two minute intervals. Arterial CO_2 pressures ($PaCO_2$) were calculated from $PetCO_2$ values using the equation $PaCO_2 = 5.5 + 0.9(PetCO_2) - 2.1(V_T)$ (Jones et al., 1979). A rating of perceived exertion (RPE) (Noble et al., 1983) was obtained at rest, after the warmup and every four minutes

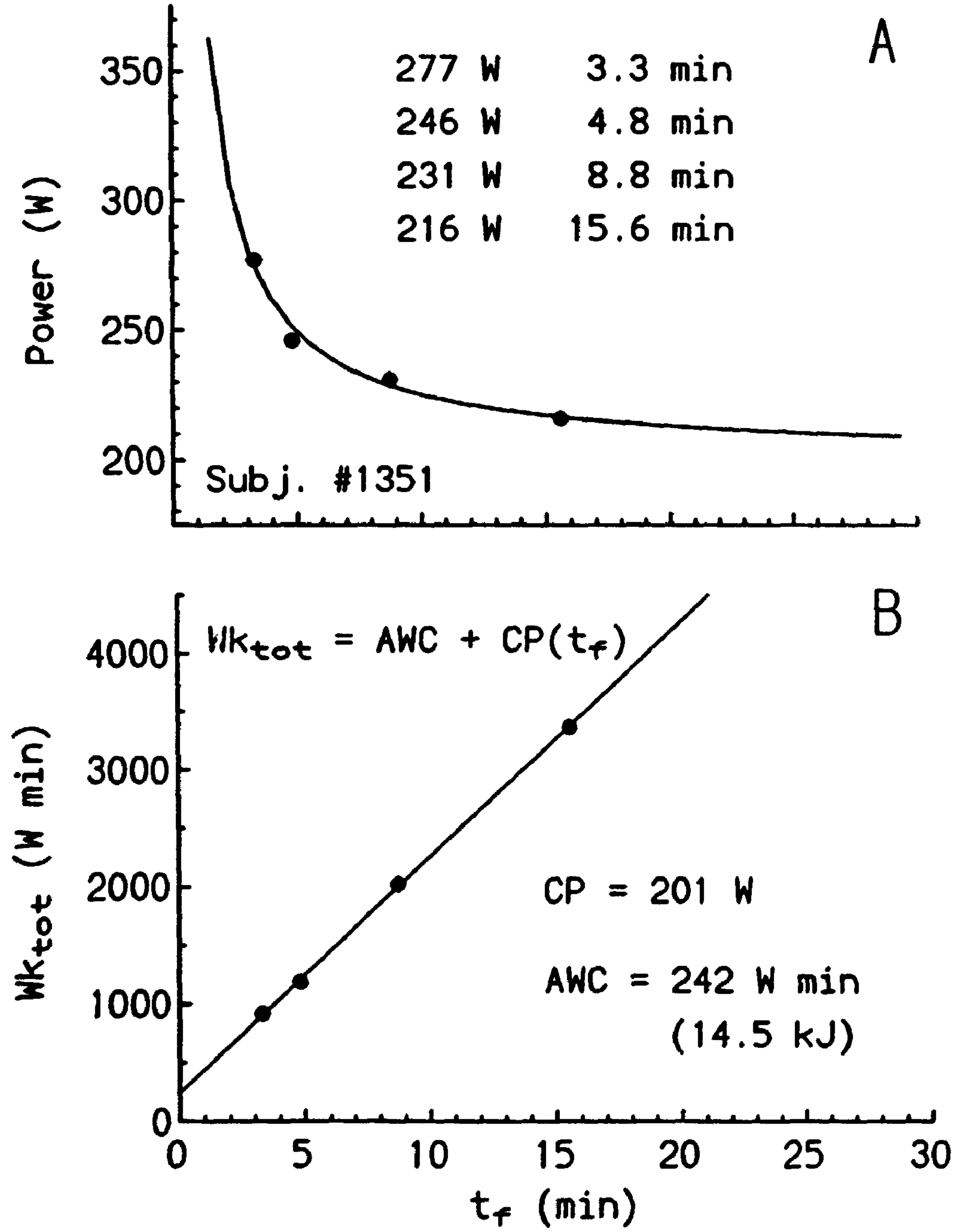


Fig. 2A Relationship between t_f and power output.

2B Determination of critical power and anaerobic work capacity from linear relationship Wk_{tot}=AWC+CP(t_f).

thereafter. Blood samples for the determination of lactate (La^-) and potassium (K^+) concentrations were drawn on the same schedule through an indwelling catheter inserted into an antecubital vein prior to the test. The collection line was kept patent with heparin infusions. Double determinations of blood lactate were made immediately following each sample (YSI Lactate Analyzer Model 23L). Readings were adjusted by a correction formula [(YSI reading - 0.2)/0.88 (YSI Model 23L Instruction Manual 1985)]. Blood samples (1.5 ml) for potassium assays were spun down following the test and the plasma drawn off into lithium coated tubes. The assays were done within one hour using a flame photometer (Radiometer Copenhagen FLM 3) with an automatic diluter.

2.2.5 Statistical Analysis

All data for the young and elderly groups were compared using non-directional independent Student's t-tests and differences were considered significant if $P < 0.05$.

2.3 RESULTS

Descriptive characteristics and the results of the ramp testing for the remaining young (n=13) and elderly (n=12) subjects are presented in Table 1. Four of the elderly men were involved in a low-level activity program (three times per week). The other elderly men were regularly active in walking, household tasks and light recreation. The young

Table 1. Descriptive subject information and results from the ramp testing.

	Young		Elderly	
Age (years)	24.5 (20-34)	(1.5)	70.7 (65-77)	(1.3)*
Height (cm)	173.9 (158.0-185.6)	(2.3)	173.8 (165.0-185.0)	(1.3)
Weight (kg)	70.0 (55.6-83.7)	(3.0)	77.1 (63.0-100.0)	(2.8)
$\dot{V}O_2max$ ($l \cdot min^{-1}$)	3.31 (2.45-4.35)	(0.15)	2.22 (1.72-2.92)	(0.12)*
$\dot{V}E$ ($l \cdot min^{-1}$)	137 (95-163)	(5)	104 (83-160)	(4)*
HR ($b \cdot min^{-1}$)	185 (162-198)	(3)	153 (134-171)	(3)*
RER	1.27 (1.16-1.45)	(0.02)	1.21 (1.06-1.49)	(0.03)
P_{max} (watts)	286 (203-385)	(14)	171 (120-265)	(13)*

Values are means ± SE, and range.
* indicates significant difference ($P < 0.05$).

subjects were active in recreational level cycling, jogging, weightlifting and various other sports. None of the subjects were involved in competitive activities and none were sedentary.

Duration of the ramp tests ranged from 8.45 to 12.20 minutes. The young subjects had significantly greater maximal values for $\dot{V}O_2$, $\dot{V}E$, HR and power output while RER at fatigue was not different between the groups (Table 1).

The results of the linear regression analyses of the Wk_{tot} vs t_f plots are presented in Table 2. In both groups, the plots yielded strong linear relationships ($r = 0.99-1.00$). The durations of the fatigue tests at the various power outputs ranged from 1.55 to 19.36 minutes. Pedalling rates varied from 75 to 95 rev·min^{-1}. CP values represented 61.9 and 66.9% of P_{max} for the young and elderly men, respectively.

All subjects were able to complete at least 24 minutes at power outputs corresponding to their CP. At 24 minutes, ratings of perceived exertion on Borg's 10 point scale ranged between 6.5 and 7.0 for the young group (7.0 = "very heavy"), and between 5.5 and 6.0 for the elderly group (5.0 = "heavy"). When asked if they could have continued, all subjects answered affirmatively, although their estimates of how much longer ranged from "a couple of minutes" to "quite a while".

Temporal profiles for $\dot{V}O_2$, $\dot{V}E$, HR, and RER all indicated significant absolute differences between the young and elderly men (Figs. 3-6). Oxygen consumption showed a rapid increase

Table 2. Comparison of CP and AWC calculated from the individual Wk_{tot} vs t_f relationships for young and elderly groups.

	Young	Elderly
Critical power (watts)	177 (10) (130-262)	115 (9)* (75-177)
Critical power (% P_{max})	61.9 (1.5) (51.2-71.1)	66.9 (0.9)* (60.6-71.9)
Anaerobic work capacity (kJ)	13.6 (1.0) (6.0-17.9)	8.1 (0.3)* (6.6-9.7)
Equations	$Wk_{tot}=226+177(t_f)$	$Wk_{tot}=135+115(t_f)$
r	1.00 (0.99-1.00)	1.00 (0.99-1.00)

Values are means (SE), and range.
* indicates significant difference ($P < 0.05$).

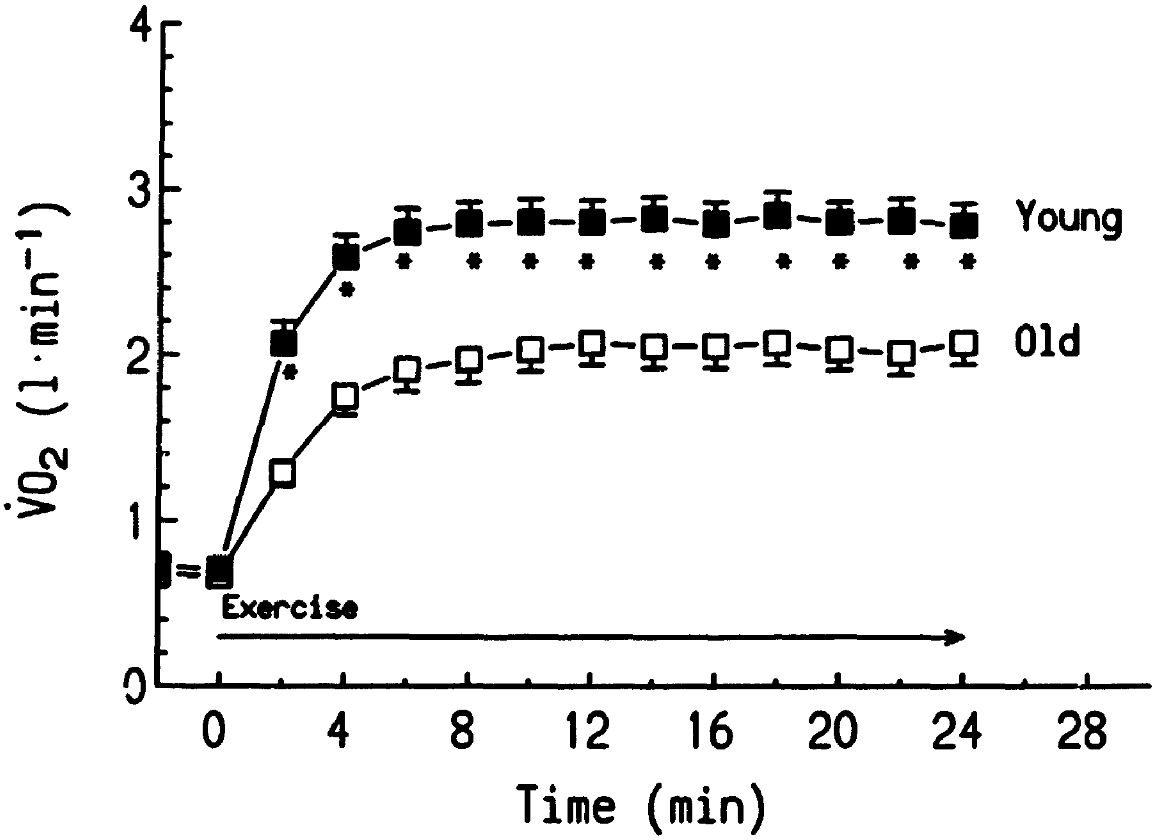


Fig. 3 Temporal profile for oxygen consumption ($\dot{V}O_2$) during the 24 minute test at critical power. Data points represent two minute averages of original data (means ± SE). * indicates significant difference between the groups.

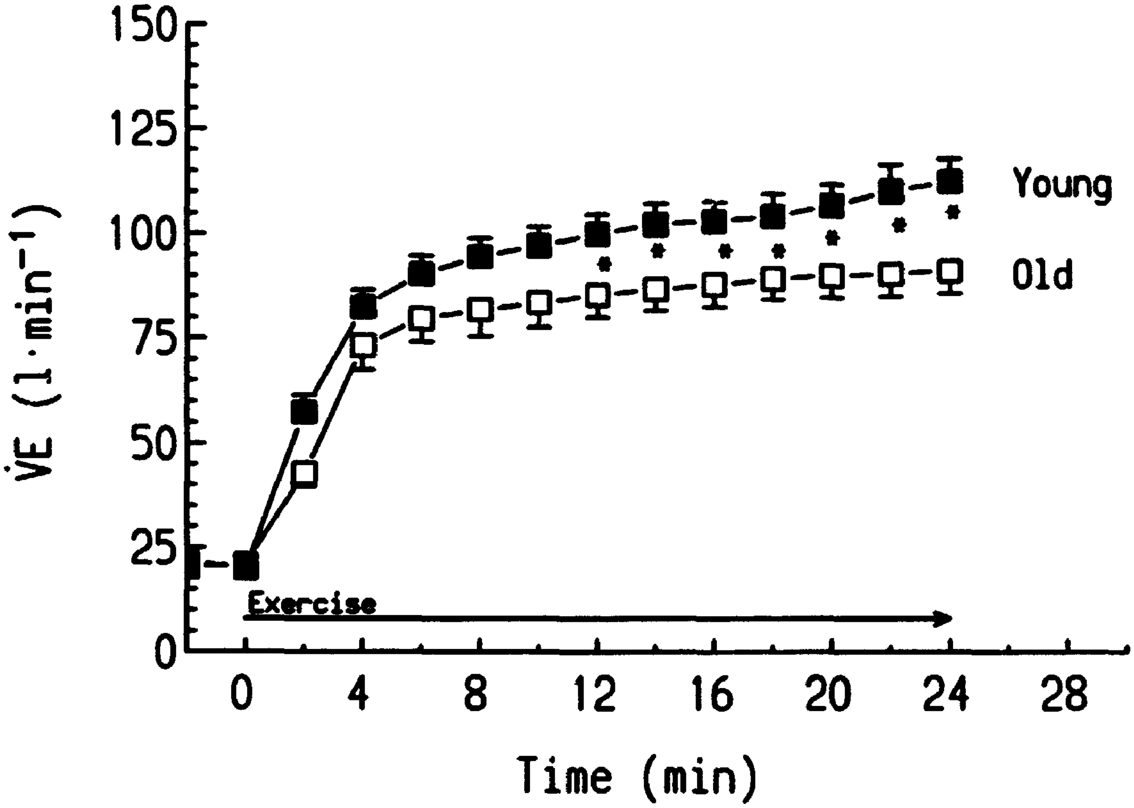


Fig. 4 Temporal profile for expired ventilation (V̇E) during the 24 minute test at critical power. Data points represent two minute averages of original data (means ± SE). * indicates significant difference between the groups.

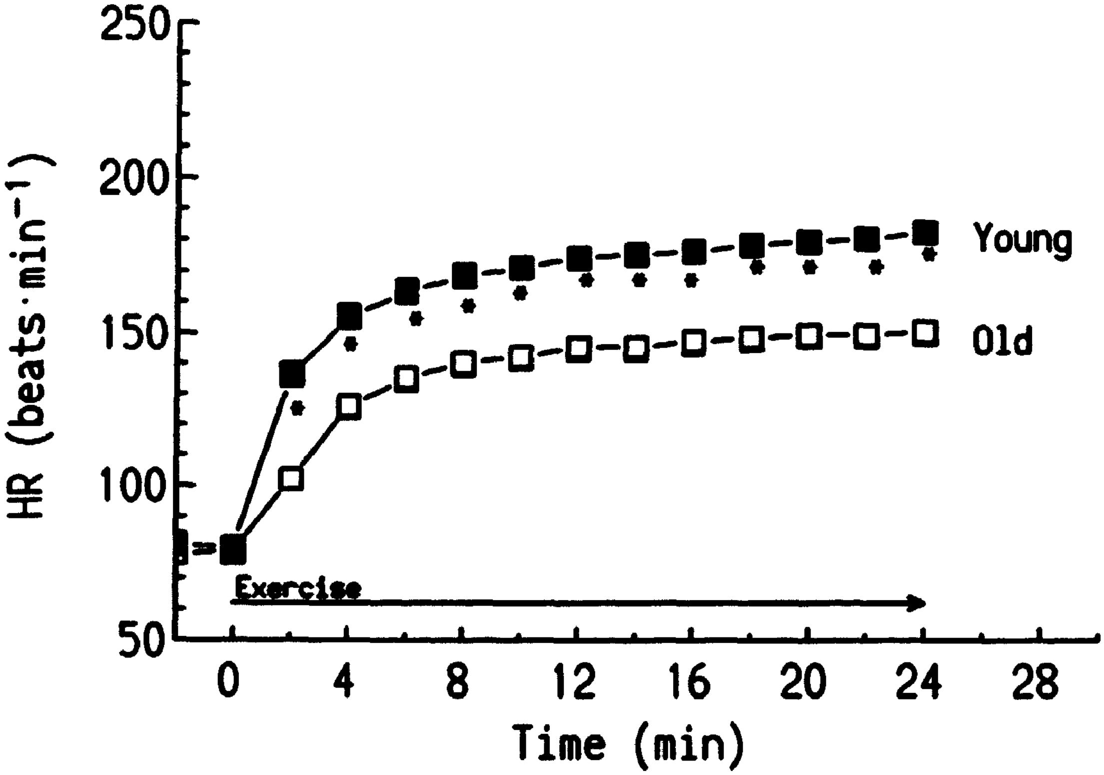


Fig. 5 Temporal profile for heart rate (HR) during the 24 minute test at critical power. Data points represent two minute averages of original data (means ± SE). * indicates significant difference between the groups.

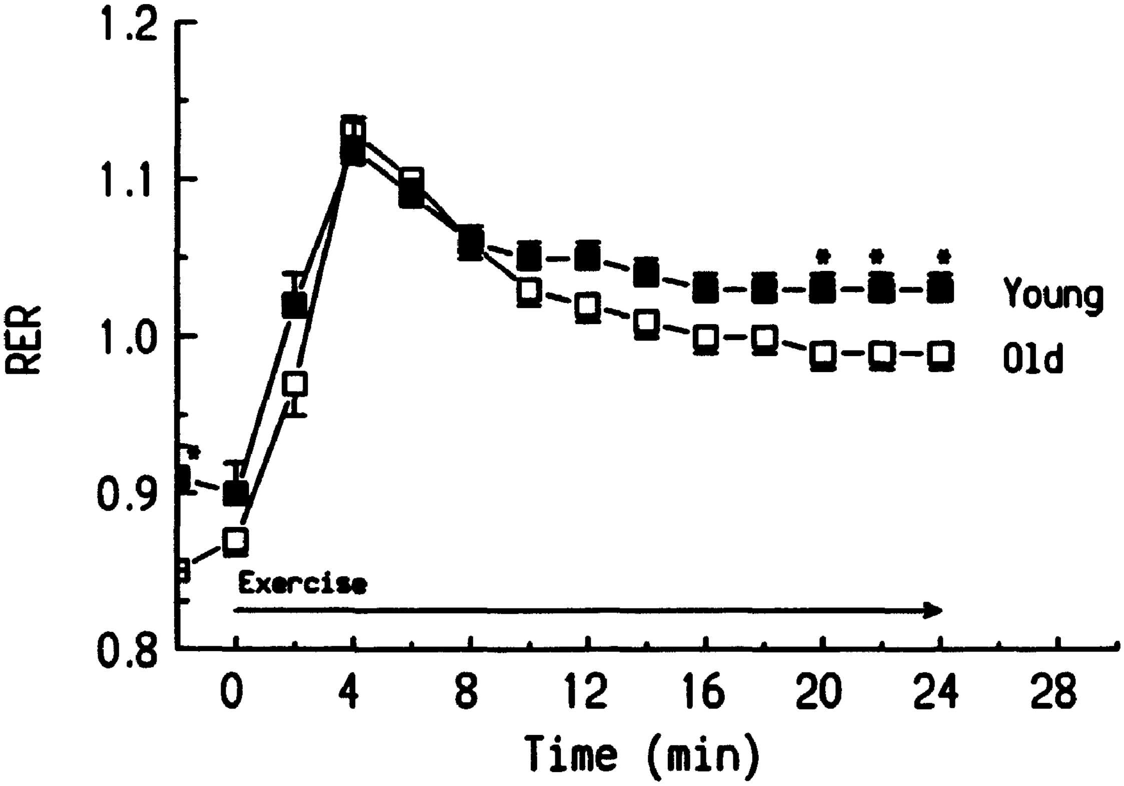


Fig. 6 Temporal profile for respiratory exchange ratio (RER) during the 24 minute test at critical power. Data points represent two minute averages of original data (means ± SE). * indicates significant difference between the groups.

at the onset of resistance and plateaued at 10 minutes, with no further increase during the balance of the test.

Profiles for blood lactate and plasma [K^+] are presented in Fig. 7. The young group reached a blood lactate peak of around 8.1 $mmol \cdot l^{-1}$ which was significantly greater than the value for the elderly group (6.5 $mmol \cdot l^{-1}$). Values for plasma [K^+] throughout the test were not different between young and elderly men.

Following a small initial rise, arterial PCO_2 values declined steadily (Fig. 8). Values for the young men were significantly higher throughout the test.

The data for seven variables were compared over the final four minutes of the test (minute 20 to minute 24) to determine if values were still changing (Table 3). A steady state for each variable was defined as no significant change. The only variable which did not reach a steady state in the elderly group was heart rate, while only $\dot{V}O_2$ and RER did attain a steady state in the young group.

Values for $\dot{V}O_2$, $\dot{V}E$, HR and RER were averaged over the last two minutes of the 24 minute test and expressed relative to maximal values for these variables achieved during the ramp testing (Table 4). The elderly group worked at a significantly higher relative $\dot{V}O_2$ during their 24 minute test.

As a means of investigating the effect of small variations from CP on time to fatigue, the power output, duration and relative values for $\dot{V}O_2$, $\dot{V}E$, HR and RER for the longest constant load test used in the determination of CP and AWC were compared to the same data from the 24 minute test (Table 5). Power outputs for the longest constant load test averaged 10% higher than CP (9% - young, 11% - elderly), leading to fatigue in 12-13 minutes.

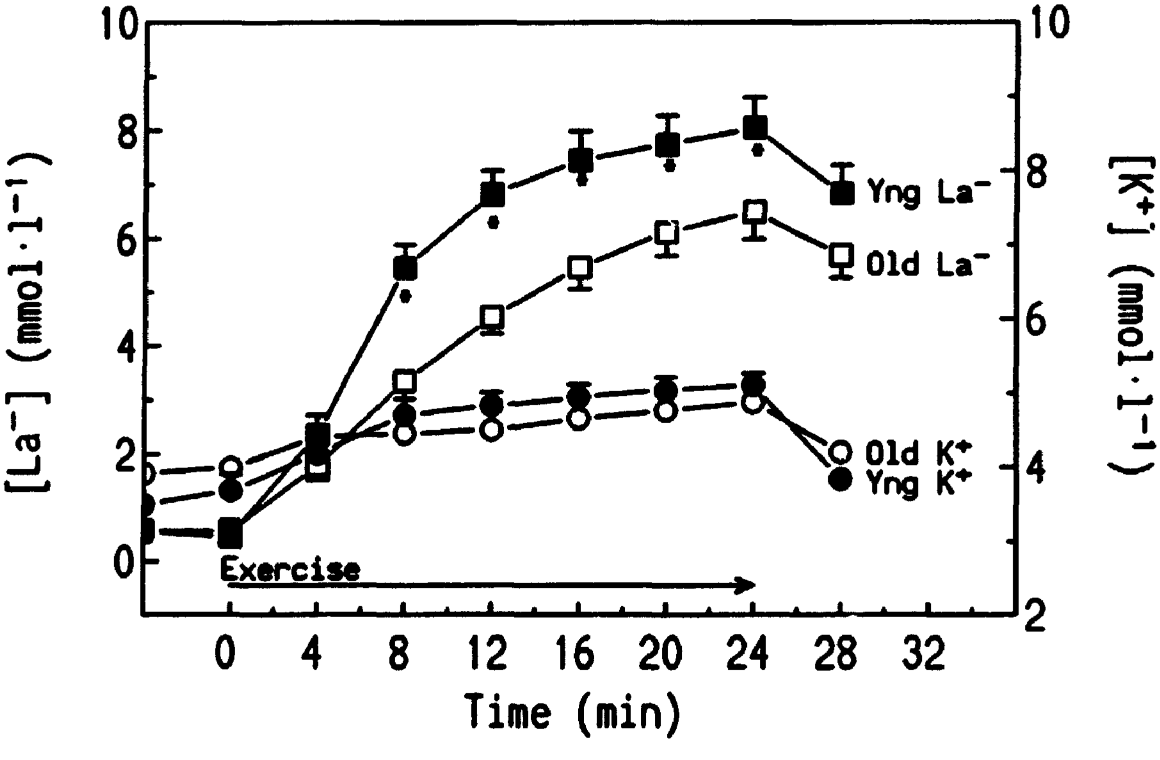


Fig. 7 Temporal profiles for venous blood lactate [La] and venous plasma potassium [K^+] during the 24 minute test at critical power (means ± SE).
* indicates significant difference between the groups.
(Yng = young)

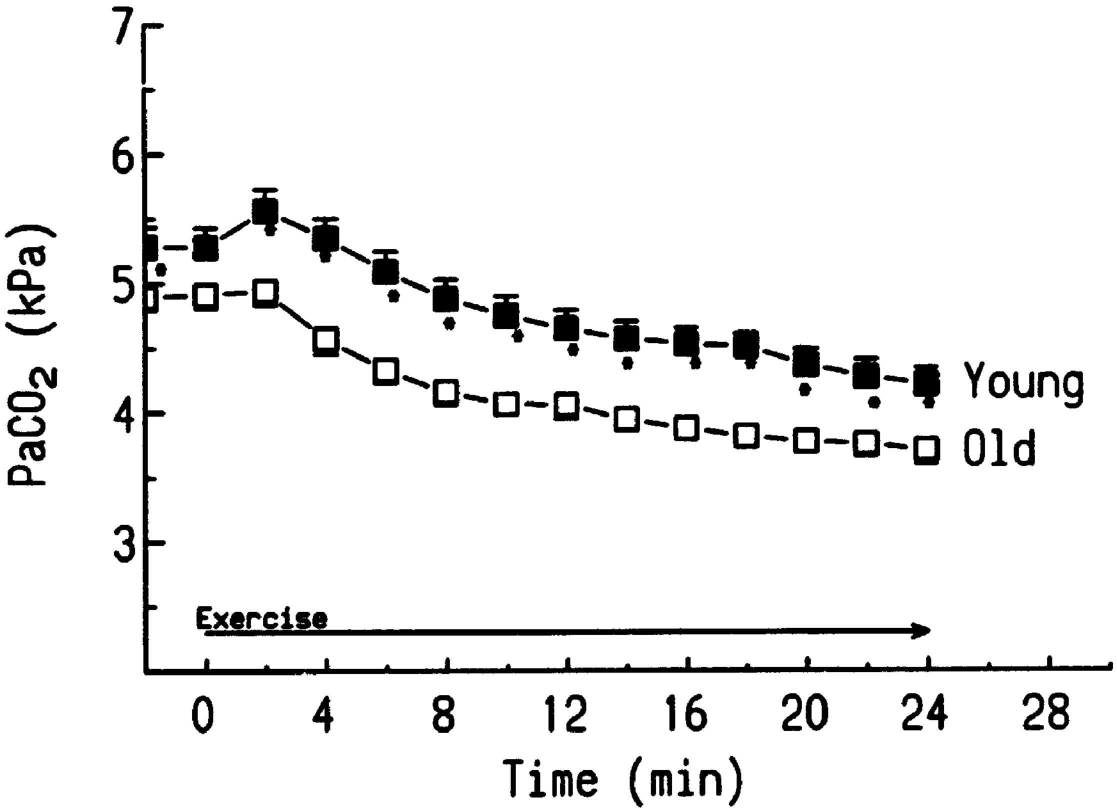


Fig. 8 Temporal profile of arterial carbon dioxide pressure ($PaCO_2$) during the 24 minute test at critical power calculated from $PetCO_2$ values [Jones et al., 1979; $PaCO_2 = 5.5+0.9(PetCO_2)-2.1(V_T)$]. Data points represent two minute averages of original data (means ± SE). * indicates significant difference between the groups.

Table 3. Comparison of mean values of data obtained from young and elderly subjects at 20 and 24 minutes during the 24 minute test.

	Young		P	Elderly		P
	20 min	24 min	value	20 min	24 min	value
$\dot{V}O_2$ $(l \cdot min^{-1})$	2.78	2.78	0.74	2.06	2.07	0.30
$\dot{V}_E$ $(l \cdot min^{-1})$	107	113	< 0.01	90	91	0.40
HR $(b \cdot min^{-1})$	179	182	< 0.01	149	150	0.02
RER	1.03	1.03	0.87	0.99	0.99	0.54
RPE	6.5	6.9	0.01	5.7	5.7	1.00
[La] $(mmol \cdot l^{-1})$	7.74	8.18	0.02	6.11	6.49	0.06
$PaCO_2^*$ (kPa)	4.37	4.22	< 0.00	3.77	3.71	0.06

RPE = rating of perceived exertion.

P value refers to probability of t-statistic determined from non-directional independent Student's t-test.

* values estimated from $PetCO_2$ values [$PaCO_2 = 5.5 + 0.9(PetCO_2) - 2.1(V_T)$, Jones et al., 1979].

Table 4. Cardiorespiratory responses (% of max) from the final two minutes of the 24 minute test relative to maximal values from the ramp testing.

	Young	Elderly
$\dot{V}O_2$ (%)	85.2 (2.0) 75.4-103.6	91.5 (1.9)$^{\bullet}$ 82.2-102.7
$\dot{V}E$ (%)	81.7 (3.7) 63.4-109.8	87.9 (3.5) 74.2-115.1
HR (%)	98.6 (1.0) 92.6-104.4	98.2 (1.5) 89.9-106.6
RER (%)	82.0 (1.8) 72.7-92.9	81.8 (1.8) 66.4-92.5

Values are means (SE), and range.
$^{\bullet}$ indicates significant difference
($P < 0.05$).

Table 5. Cardiorespiratory responses (% of max from ramp test) during the longest constant load test to fatigue (CL) and the 24 minute test (24).

		Young	Elderly
$\dot{V}O_2$ (%)	CL	93.7 (1.9)	97.2 (2.1)
	24	85.2 (2.0)*	91.5 (1.9)†
$\dot{V}E$ (%)	CL	104.4 (4.0)	96.3 (2.7)
	24	81.7 (3.7)*	87.9 (3.5)*
HR (%)	CL	99.2 (0.9)	101.2 (1.5)
	24	98.6 (1.0)	98.2 (1.5)
RER (%)	CL	83.8 (1.3)	85.0 (2.1)
	24	82.0 (1.8)	81.8 (1.8)*
Power (%)	CL	68.5 (1.0)	73.8 (0.7)†
	24	61.9 (1.5)*	66.9 (0.9)*†
Time (min)	CL	11.8 (0.7)	12.8 (1.0)
	24	24.0 (0.0)*	24.0 (0.0)

Values are means (SE).
* indicates significantly different than (CL).
† indicates significantly different from Young group ($P < 0.05$).

2.4 DISCUSSION

The present study has demonstrated that CP and AWC can be determined in elderly subjects. Despite the rigours of the testing protocol necessary to determine CP and AWC, all of the elderly men were able to complete the required tests without incident. The similarly high correlation coefficients between Wk_{tot} and t_f in both young and elderly men (Table 2) indicate that the elderly men were equally able to push themselves to consistent voluntary fatigue at the four different power outputs.

The $\dot{V}O_2$max values for the active young and elderly men in the present study were appropriately higher than values reported previously for sedentary groups of subjects (Hagberg et al., 1988; Chick et al., 1991). Anaerobic work capacity values for the young subjects in the current study are similar to those reported previously (Moritani et al., 1981; Poole et al., 1988; Housh et al., 1989), while the values for CP were approximately 10% lower. The lower CP values probably reflect the lower $\dot{V}O_2$max of the young subjects [3.31 l·min^{-1} vs 3.66 (Housh et al.), or 3.81 (Poole et al.)]. It may also reflect the fact that the young subjects in the present study chose to pedal at rates around 80-90 rev·min^{-1}. Carnevale and Gaesser (1991) have recently shown that a protocol of constant load tests at 60 rev·min^{-1} results in derived CP values 16% higher than values derived from a protocol at 100 rev·min^{-1}.

Mean CP for the elderly subjects was significantly lower than the young group. Compared to the young men, the elderly values were 65% and 67% of CP and $\dot{V}O_2$max, respectively. CP and $\dot{V}O_2$ are closely related indices of aerobic function. CP has been significantly correlated with $\dot{V}O_2$max in younger subjects ($r = 0.92$, Moritani et al., 1981; $r = 0.84$, Hughson et al., 1984). However, the CP work rate for the elderly (115 W) represented 67% of their maximal power output attained during the ramp testing, and was significantly greater than the 62% P_{max} attained by the young men, suggesting that the maximal rate of non-fatiguing work in elderly men may occur at a higher relative work rate. While P_{max} on a ramp test may be dependent upon the slope of the ramp (Davis et al., 1982), this effect is only apparent at much steeper slopes than were used in the current study for either young or elderly men. Thus, it appears that the elderly men in the present study were capable of similar or higher relative work rates than the young men for at least a 24 minute period.

The AWC of the elderly men was 60% that of the young men. Although not assessed in the current study, the previously documented age-related decreases in anaerobic power and capacity (Makrides et al., 1985), and quadriceps size (Klitgaard et al., 1990), knee extensor strength (Young et al., 1985), and knee extensor endurance (Nakao et al., 1989) may explain this difference. Anaerobic work capacity (Nebelsick-Gullett et al., 1988) and knee extensor strength

(Thorland et al., 1987) have previously been significantly correlated with anaerobic capacity (Wingate test).

The elderly men in the present study were as capable as the young men in maintaining exercise at power outputs corresponding to CP. Every elderly subject was able to complete at least 24 minutes at CP even though CP in the elderly men occurred at a significantly higher relative power output (Table 2), and elicited a significantly higher relative $\dot{V}O_2$ (Table 4). Although relative $\dot{V}O_2$ and work rate at CP were higher in the elderly group, there were no differences in relative $\dot{V}E$, HR, or RER at the end of the 24 minute test. Blood lactates were higher in the young men, but were not measured during the ramp testing so that comparisons relative to maximal values can not be made. Potassium has recently been linked to skeletal muscle fatigue (Lindinger and Sjogaard, 1991), but no differences were observed between the venous plasma $[K^+]$ in the young and elderly men throughout the 24 minute test in the present study. The values for $PaCO_2$ were higher for the young men throughout the test. This might be due to the fact that the equation (Jones et al., 1979) used to convert $PetCO_2$ to $PaCO_2$ was derived from data on younger subjects. Dead space is also higher in the elderly.

There are at least two possible explanations for the higher relative $\dot{V}O_2$ in the elderly men. The first is that the elderly men failed to reach a true maximal value during the ramp testing. Since the data in Table 4 are expressed relative to maximal values established in the ramp testing, the ability of a ramp test to elicit maximal physiological responses must be considered when evaluating significance. Each subject performed two ramp tests and data from the test eliciting the greatest $\dot{V}O_2$ were assumed to represent maximal values. No learning effect was evident as one third of the subjects attained their highest $\dot{V}O_2$ on each of the two tests, while the final third attained a similar score on both tests.

Over half of the subjects achieved a plateau in $\dot{V}O_2$ during the two ramp tests (18 of 26 young, 11 of 23 elderly). Although the young men were better able to reach a plateau, this does not necessarily suggest a failure of the elderly to reach a maximal $\dot{V}O_2$. The necessity of attaining a plateau in the $\dot{V}O_2$ response to incremental exercise in order to determine a true $\dot{V}O_2$max has been challenged (Noakes, 1988) and Myers et al. (1990) recently reported that considerable variability existed in the slope of change of $\dot{V}O_2$ with a consistent change in external work. They suggested that the existence of a plateau during ramp exercise is not a reliable physiological indicator of maximal effort. Thus, the lack of a $\dot{V}O_2$ plateau in some of the subjects in the present study may not indicate less than maximal effort. This may be particularly true in the elderly who might not possess the capacity for sustained anaerobic work necessary to elicit a plateau. The high maximal HR and RER values during the ramp testing (Table 1) provide further evidence that these subjects exercised to maximum. Despite this evidence however, some of the subjects did reach a higher $\dot{V}O_2$ during the constant load testing used to determine CP and AWC. This phenomenon was also observed by Poole et al. (1988) in young subjects and may reflect inherent differences between ramp and constant load testing.

A second explanation is that elderly men may in fact be able to work at a higher percentage of their $\dot{V}O_2$max. Allen et al. (1985) found this to be true in well trained elderly runners. These men were able to run at 92% of $\dot{V}O_2$max during a 10 km run, significantly higher than the 81% elicited from a matched group of younger runners. This second explanation is further supported by the fact that decreases in $\dot{V}O_2$max with age are greater than the losses in submaximal exercise capacity (eg. ventilation threshold) (Thomas et al., 1985).

It may also be that CP occurred at a higher relative power output and $\dot{V}O_2$ in elderly men because their anaerobic capacity was only about 60% that of the young men. This suggests that although elderly men might perform equally well at CP, they would fatigue more quickly at any power output greater than CP. Further study of exercise at such power outputs is needed to evaluate this suggestion.

The second purpose of the present study was to examine the nature of the non-fatiguing work rate that CP is supposed to represent. Theoretically, work can be continued indefinitely at work rates at or below CP, although in practice, very long duration work will be limited by problems of substrate depletion, temperature regulation and fluid and electrolyte balance. A true non-fatiguing work rate is one at which steady state physiological responses are elicited. Under these criteria, CP as determined in the present study may not represent a non-fatiguing work rate, although the young and elderly groups did show slightly different temporal response patterns. $\dot{V}O_2$ and RER attained plateaus in both groups, but in the young group, $\dot{V}E$, RPE, HR, and blood lactate continued to rise throughout the 24 minute test while $PaCO_2$ continued to fall, indicating a non-steady state condition. HR was the only variable to increase until the end of the test in the elderly group although the drift over the final four minutes was only one $b \cdot min^{-1}$. This apparent difference in response patterns between the groups should be interpreted with caution, however, as changes approached significance for both blood lactate (P=0.06) and $PaCO_2$ (P=0.06) in the elderly group (Table 3). Support for the possibility that elderly men respond differently to prolonged high-intensity constant load exercise was provided recently by Chick et al. (1991) who reported that the upward drift in $\dot{V}O_2$, $\dot{V}E$ and HR during 10 minutes of exercise at 70% P_{max} was reduced in elderly men compared to matched young subjects. The data in the current study for $\dot{V}E$ and HR would support these observations. Chick et al. suggested that the reduced upward drift in the elderly was due to an attenuated glycolytic response to adrenergic stimulation and/or to a selective loss of type II muscle fibres.

No previous studies have examined responses to prolonged exercise at CP in elderly men. However, the metabolic and respiratory profiles of exercise at CP and CP+5% have been documented in young men (Poole et al., 1988). At CP, $\dot{V}O_2$ reached a plateau of 79% $\dot{V}O_2$max but $\dot{V}E$, blood lactate and breathing frequency continued to rise while $PaCO_2$ continued to drift downwards. Data for the young men in the present study are consistent with these observations. At CP+5%, subjects of Poole et al. (1988) could only ride for an average of 17.7 minutes with a $\dot{V}O_2$ at fatigue of 97% $\dot{V}O_2$max. $\dot{V}E$ and blood lactate rose steadily until fatigue while $PaCO_2$ and pH fell.

Housh et al. (1989) determined CP in a group of young men and then measured actual time to fatigue at various percentages of CP. They arbitrarily terminated exercise at 60 minutes for an intensity of CP minus 20%. Their subjects fatigued around 33 minutes at CP and power curve analyses revealed that CP overestimated the power output which could be maintained for 60 minutes by a mean of 17%. Unfortunately, no cardiorespiratory or metabolic data were reported in this study.

The results of previous studies which have determined time to fatigue at various percentages of CP in young men are summarized in Fig. 9. The average power output of the longest constant load test used to determine CP in the present study

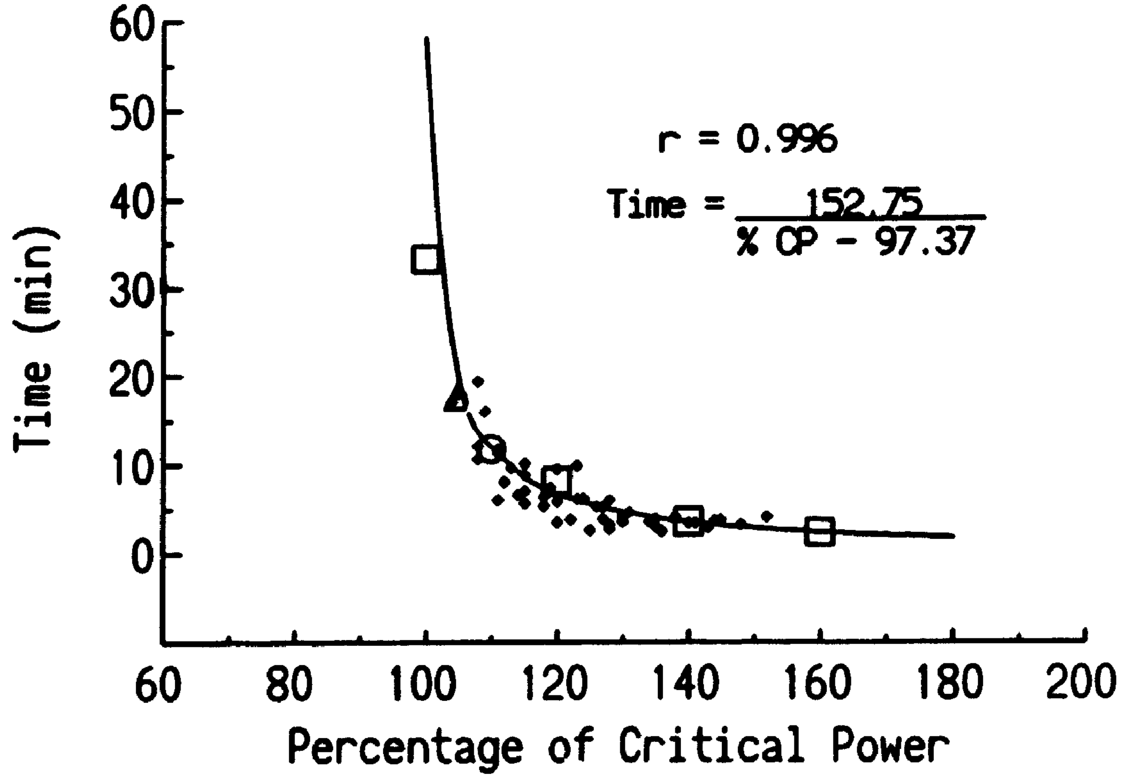


Fig. 9 Summary figure of data from studies that have determined time to fatigue at different percentages of critical power. The triangle (Poole et al., 1988), squares (Housh et al., 1989) and circle (current study) represent mean data from young men. Solid diamonds represent individual data from the elderly men in the current study.

was approximately CP+10%. Within the limitations of data summarized in this way, it is clear that CP represents some type of intensity threshold for constant load exercise. While CP may not reflect a true non-fatiguing work rate, time to fatigue appears to be quite sensitive to small increases above this demarcation point. Although no previous studies have determined time to fatigue at work rates greater than CP in elderly men, the individual data for the elderly men in the present study (Fig. 9) suggest that the relationship between time to fatigue and power outputs greater than CP may not be altered by age.

It has been suggested (Rusko et al., 1986) that the lactate threshold represents the upper limit of power output where lactate production and removal is in equilibrium. A lactate threshold was not determined in the current study, but given that blood lactate increased steadily throughout the 24 minute test and that previous studies (Ribeiro et al., 1986; Aunola et al., 1990; Mognoni et al., 1990) have shown that exercise at the lactate threshold (70-80% $\dot{V}O_2$max) can be continued for 40-60 minutes, it seems clear that CP represents an intensity threshold above the lactate threshold. Rather than representing a true non-fatiguing work rate, CP may more likely represent a demarcation point between the "heavy" and the "severe" domains of exercise (Whipp, 1987), such that, while power outputs greater than CP lead inexorably to fatigue, power outputs less than or equal to CP can be maintained for prolonged periods even though indicators of physiological stress continue to increase.

In conclusion, the results of the present study indicate that, within the limitations of the study sample, CP and AWC can be determined in active elderly men. It has also been shown that CP may not represent a true non-fatiguing work rate in either young or elderly men, although it appears that the physiological response pattern of elderly men to prolonged work at CP may differ from that of young men. Further studies of exercise to fatigue at CP, and at work rates slightly above and below CP are needed to further investigate potential age-related differences in these physiological response patterns.

CHAPTER THREE

THIGH COMPOSITION IN YOUNG AND ELDERLY MEN DETERMINED BY COMPUTED TOMOGRAPHY

3.1 INTRODUCTION

It is well established that muscular strength declines with age (Grimby and Saltin, 1983; Borges, 1989). Training studies have demonstrated, however, that the elderly show dramatic improvements in strength (Aniansson and Gustafsson, 1981; Frontera et al., 1988; Fiatarone et al., 1990). These improvements have been attributed to changes in both muscle mass (Aniansson and Gustafsson, 1981; Frontera et al., 1988) and neural activation (Moritani and deVries, 1980; Fiatarone et al., 1990).

Quantification of changes in muscle mass must be performed accurately in order to relate changes in strength to changes in muscle size. Girth measurements do not give definitive information regarding changes in limb composition which may accompany changes in muscular strength. Ageing is accompanied by an increase in the amount of subcutaneous fat, intra-muscular fat, and other non-muscle tissue (NMT) (Rice et al., 1988). Thus, while the composition of a limb may change with age, limb girth may not. More precise imaging techniques such as ultrasound, computed tomography (CT) and nuclear magnetic resonance (NMR) must be employed in studies investigating the response of elderly men and women to strength training programs in order to draw meaningful conclusions.

The knee extensor and flexor muscles in the thigh are critical to many every day activities as well as to most modes of locomotion. The quadriceps and hamstring muscle groups enable people to climb and descend stairs, sit down in and get up from chairs as well as walk, jog, run and cycle. Despite the importance of these muscles, especially in the elderly who wish to remain living independently (Aniansson et al., 1980), few previous studies have attempted to precisely quantify cross-sectional areas (CSA) or volumes of the quadriceps or hamstring muscle groups. Studies employing imaging techniques have generally been limited to a single scan, usually at the level of greatest girth to determine total thigh CSA, or less frequently, quadriceps CSA (Haggmark et al., 1978; Bulcke et al., 1979; Jones et al., 1983; Hudash et al., 1985). Even fewer studies have been carried out on elderly subjects (Borkan et al., 1983; Schwartz et al., 1990; Sipila and Suominen, 1991a). In scanning the recent literature, hamstring CSA, and volume estimates of the hamstring and quadriceps muscle groups, which require multiple scans, have never been determined in the elderly.

Previous work from this laboratory established component CSA and volumes in the leg and upper arm (Rice et al., 1988). This work was extended in the present study by taking multiple CT scans of the thigh from groups of young and elderly men in order to determine and compare CSA of the quadriceps and hamstring muscle groups, and the subcutaneous and intramuscular fat deposits. In addition, geometric equations were used to estimate the volumes of these thigh components.

3.2 METHODS

Subject selection procedures were as described in Chapter One (p.9). Measures of height, weight, thigh length of the dominant (kicking) leg, and thigh girth were obtained using standard anthropometric techniques. Thigh length was defined as the distance between the superior border of the patella and the most proximal place where a thigh girth could be obtained (gluteal fold). Thigh length was obtained using an anthropometer with the subjects in standing position. Thigh girth was obtained using a flexible nylon tape calibrated against a metal metre stick. Thigh girth was taken at the level where a normal front thigh skin fold is obtained (Lohman et al., 1988).

3.2.1 Computed Tomography

A series of five scans in descending order were taken from the dominant leg of each subject. The most proximal and most distal scans were located as described above. A third scan was taken at the level of the thigh girth measure thus creating two segments, usually of unequal length. The last two scans were located at the midpoints of each of these two segments. The scan sites were marked on the skin and the distances between each scan location were determined with an anthropometer.

The scans were taken with the subject supine on the scanner bed. Pillows were used under the subject's feet and buttocks in order to minimize any tissue compression in the thigh. A light beam in the scanner gantry aligned the scan with the marks on the thigh. The scanner (Siemens Somatom DRH) made a 4mm scan (4 sec/scan) over a 360 degree scan angle using exposure settings of 125 kVp and 280mAs/projection.

All diagnostic radiology techniques involve some risk from ionizing radiation. Radio-sensitive tissues in this study were red bone marrow and bone. A lead glove was used to shield the gonads. The risk of developing a fatal cancer from the radiation absorbed in this study was estimated at approximately twice the annual risk due to natural background radiation where the subjects live.

3.2.2 Data Analysis

Scan images (256 x 256 pixel matrix) were stored for subsequent analysis using a BSP 11 image computer linked with a PDP 11/24 computer. A pen cursor was used to outline regions of interest on each scan including total thigh area (TTA), total muscle plus bone area (MBA), quadriceps compartment area (QCCSA), hamstring compartment area (HCCSA) and bone area (BNA). A measure for skin plus subcutaneous fat area (SSCFA) was obtained by subtraction. In both the quadriceps and hamstring compartments, an area measure of non-muscle tissue (NMT) (fat plus loose connective tissue) was obtained by computer highlighting based on a reduced density compared to muscle. The density range in this study for NMT was from -125 to 25 Hounsfield units (HU). Average muscle density depends somewhat on the CT system, but values for quadriceps and hamstrings from 50-80 HU have been previously reported (Bulcke et al., 1979; Termote et al., 1980; Jones et al., 1983). Quadriceps (QCSA) and hamstring (HCSA) areas were calculated by subtracting NMT areas from the related muscle compartment area. Since CT scanning does not allow a clear distinction between muscle and tendon, all tissue compartments referred to as muscle include both tendon and muscle. Similarly, the subcutaneous fat measure includes some vascular structures.

To determine the mechanical error associated with the scanner system, a plexiglass and water phantom of known diameter was scanned and then digitized. The error was determined to be < 0.4%. Reproducibility of measurement was determined by randomly measuring 25 thigh component areas a second time. The average intra-observer difference was 2.2%. A second observer also repeated area measurements on 12 muscle regions from different scans. The inter-observer error was 3.8%.

Segmental thigh component volumes were determined using the formula of Jones and Pearson (1969) for truncated cones. The formula is $V = 1/3\ h\ (a + \sqrt{ab} + b)$ where V is the segment volume, h is the length of the segment, and a and b are the cross-sectional areas of each end of the segment. The four segmental component volumes were then summed to give total volumes for the thigh (TTVOL), muscle plus bone (MBVOL), quadriceps (QDCVOL) and hamstring (HSCVOL) compartments, and bone (BNVOL). Quadriceps (QDVOL) and hamstring (HSVOL) muscle volumes, less any NMT, and skin plus subcutaneous fat (SSCFVOL) volumes were calculated by subtraction.

3.2.3 Statistical Analysis

Area and volume measurements for the young and elderly groups were compared using non-directional independent Student's t-tests. Predictions for component volumes from single scan CSA measurements and thigh length were derived using stepwise multiple linear regression (SPSS/PC, 1984).

3.3 RESULTS

The CT data for one elderly subject could not be used for technical reasons, thus data are presented here on only 11 elderly subjects. Thigh length in the young men was significantly greater (Table 6) although there was no difference in overall height. Typical CT images of quadriceps and hamstring muscle groups in young and elderly men are shown in Fig. 10 and Fig. 11.

Table 7 shows the results of the thigh component CSA measures. The TTA, MBA, and QCCSA were taken from the third scan, corresponding to the largest quadriceps area measure. The HCCSA and BNA measures were taken from the fourth scan, corresponding to the largest hamstring area measure. MBA was significantly smaller in the elderly group. Since there was no group difference in TTA, this resulted in a significantly larger SSCFA in the elderly men (Figs. 10 and 11). QCCSA, QCSA, HCCSA, and HCSA measures were all significantly smaller in the elderly men. However the NMT areas in each muscle compartment were significantly larger.

Estimated thigh component volumes are presented in Table 8. TTVOL was significantly larger in the young men due to their greater thigh length, since mid-thigh girths were not different (Table 6). Despite this difference in TTVOL, the elderly men still had significantly larger NMT volumes in both the quadriceps and hamstring compartments.

Variables of thigh length, thigh component CSA and age group were entered into the multiple regression analysis. All predictive variables included in the equations (Table 9) were independently and significantly related to the indicated dependent variable. For all volumes except TTVOL and BNVOL, the relevant component CSA entered first into the equation and contributed between 52 and 84% of the explained variance. The

Table 6. Subject characteristics.

	Young (n=13)	Elderly (n=11)
Age (years)	24.5 ± 1.5 (19-34)	71.0 ± 1.4* (65-77)
Height (cm)	173.9 ± 2.3 (158.0-185.6)	173.9 ± 1.8 (165.0-185.0)
Weight (kg)	70.0 ± 3.0 (55.0-83.7)	75.0 ± 2.1 (63.0-87.3)
Thigh length (cm)	26.9 ± 0.7 (21.8-30.6)	24.6 ± 0.7* (22.0-29.0)
Thigh girth (cm)	52.7 ± 1.7 (46.0-68.8)	50.5 ± 0.6 (47.3-53.6)

Values are means ± SE, and range in brackets.
* indicates significant difference ($P < 0.05$)
Thigh girth taken at mid-thigh skinfold location.

Fig. 10 CT scan at greatest girth of quadriceps muscles from 20 year old man (left) and 65 year old man (right). Quadriceps area is outlined and non-muscle tissue is highlighted.

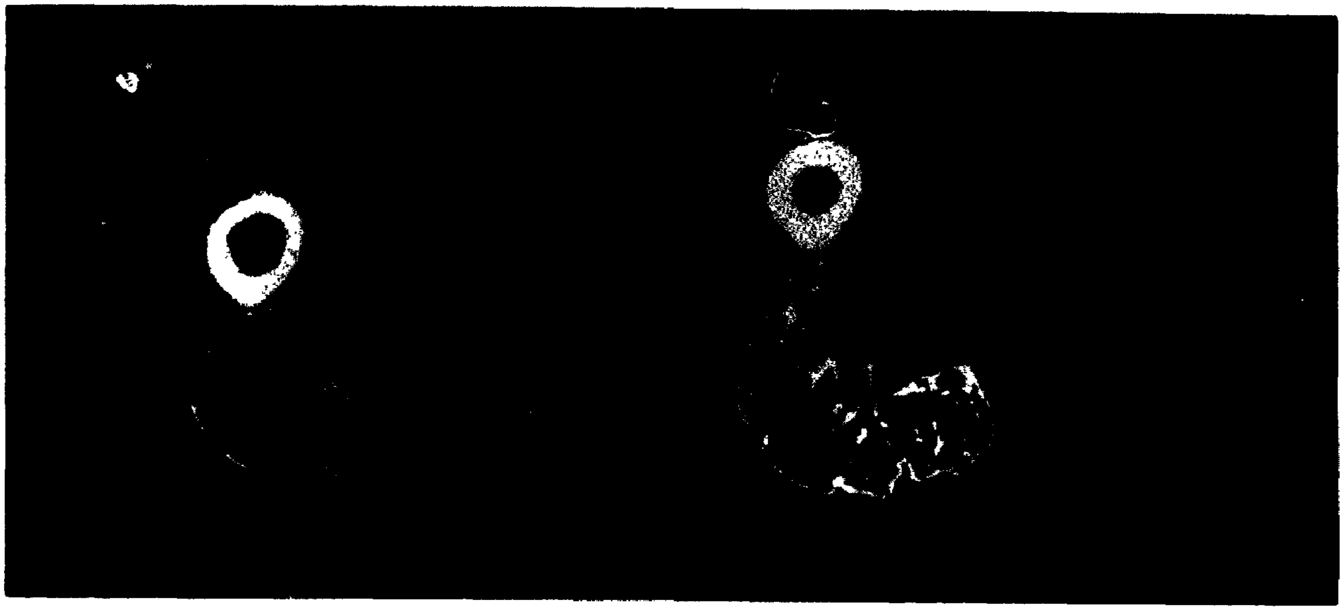


Fig. 11 CT scan at greatest girth of hamstring muscles from 20 year old man (left) and 65 year old man (right). Hamstring area is outlined and non-muscle tissue is highlighted.

Table 7. Cross-sectional areas of thigh components measured from computed tomography (CT) scans.

Limb component (cm^2)	Young (n=13)	Elderly (n=11)	P value
Total thigh	220.5 ± 10.1 (171-292)	211.2 ± 4.5 (191-233)	0.41
Muscle plus bone	182.2 ± 7.7 (140-223)	158.5 ± 4.1 (142-187)	< 0.01
Skin + subcutaneous fat	38.3 ± 4.0 (20-69)	52.7 ± 4.0 (36-73)	0.02
Quadriceps compartment	88.2 ± 4.0 (68.8-115)	69.0 ± 2.6 (60-86.6)	< 0.01
NMT in Quadriceps compartment	3.2 ± 0.3 (1.6-5.6)	5.1 ± 0.7 (3.3-6.7)	< 0.01
Quadriceps muscles	84.7 ± 3.8 (66-111.1)	63.9 ± 2.6 (54.2-80.4)	< 0.01
Hamstrings compartment	40.7 ± 2.0 (30.6-52.6)	36.6 ± 2.6 (30.6-47)	< 0.01
NMT in Hamstrings compartment	2.2 ± 0.2 (1.3-3.3)	5.0 ± 0.3 (3.6-6.4)	< 0.01
Hamstring muscles	38.5 ± 1.9 (29.3-50.1)	31.6 ± 1.6 (25.6-43.5)	0.01
Bone	8.5 ± 0.3 (6.3-9.7)	8.7 ± 0.3 (7.1-10.6)	0.65

Values are means ± SE, and range in brackets.

NMT is non-muscle tissue.

P value refers to probability of t-statistic determined from non-directional independent Student's t-test.

All measurements were made from mid-thigh CT scan except bone and hamstring values which were taken from the next distal scan.

Table 8. Estimated thigh component volumes.

Thigh Component (cm^3)	Young (n=13)	Elderly (n=11)	P value
Total thigh	5223.8 ± 200.1 (3949.6-6177.2)	4520.4 ± 162.4 (3706.1-5382.4)	< 0.01
Muscle plus bone	4219.4 ± 156.6 (3410.5-4883.5)	3355.1 ± 136.6 (2742.9-4180.9)	< 0.01
Skin+subcutaneous fat	1004.4 ± 81.7 (539.1-1440.7)	1165.3 ± 70.4 (725.4-1571.7)	0.15
Quadriceps compartment	1902.6 ± 81.8 (1450.1-2287.3)	1396.5 ± 62.2 (1077.3-1764.9)	< 0.01
NMT in Quadriceps compartment	98.0 ± 8.6 (65.5-165.3)	140.0 ± 9.3 (100.5-206.1)	< 0.01
Quadriceps muscles	1804.7 ± 77.9 (1372.2-2161.9)	1256.4 ± 62.1 (925.4-1624.7)	< 0.01
Hamstrings compartment	771.7 ± 41.9 (605.5-1059.0)	648.4 ± 26.0 (550.5-859.5	0.02
NMT in Hamstrings compartment	59.8 ± 4.5 (41.3-93.2)	120.7 ± 7.1 (81.0-166.1)	< 0.01
Hamstring muscles	711.9 ± 39.4 (546.9-1000.5)	527.7 ± 28.0 (407.1-765.9)	< 0.01
Bone	239.7 ± 9.9 (175.5-281.6)	225.6 ± 10.5 (181.4-275.3)	0.34

Values are means ± SE, and range in brackets.

NMT is non-muscle tissue.

P value refers to the probability of t-statistic determined from non-directional independent Student's t-test.

Volumes are sums of four segmental volumes calculated from area and length measures of five CT scans.

Table 9. Prediction of thigh component volumes in young and elderly men from thigh lengths and thigh component cross-sectional areas from single CT scans.

Dependent variable	Independent variable	R^2(%)
Total thigh volume	= 218.7 (thigh length) + 17.9 (thigh CSA) - 4620.1 SEE = 176.6 cm^3 (3.6%)	94.1
Muscle plus bone volume	= 18.4 (muscle + bone CSA) + 168.9 (thigh length) - 3683.4 SEE = 139.8 cm^3 (3.7%)	95.7
Quadriceps comp. volume	= 18.8 (quadriceps comp. CSA) + 60.2 (thigh length) - 1371.5 SEE = 73.9 cm^3 (4.4%)	95.8
Quadriceps muscle volume	= 19.2 (quadriceps muscle CSA) + 56.5 (thigh length) - 1352. SEE = 77.9 cm^3 (5.0%)	95.6
Hamstrings comp. volume	= 18.3 (hamstring comp. CSA) + 14.3 (thigh length) - 366.7 SEE = 56.9 cm^3 (8.0%)	83.0
Hamstring muscles volume	= 19.4 (hamstring muscles CSA) + 13.5 (thigh length) - 407.2 SEE = 52.4 cm^3 (8.3%)	88.1
Bone volume	= 10.3 (thigh length) + 18.9 (bone CSA) - 193 SEE = 10.0 cm^3 (4.3%)	92.0

Volumes are in cm^3, CSA (cross-sectional area) is in cm^2 and thigh length in cm. SEE = standard error of estimate. R^2 is percentage of total explained variance. Comp = compartment.

All CSA are from mid-thigh CT scan except hamstrings and bone CSA which are from next distal scan.

All independent variables were significantly ($P \leq 0.01$) related to the dependent variable.

second variable, thigh length, added between 5 and 48% to the total explained variance. For TTVOL and BNVOL, thigh length was the best explanatory variable, accounting for 46 and 68% of the variance, respectively. Thigh length was followed by component CSA which added 48% to the total variance for TTVOL and 25% to BNVOL. The variable, age group, did not enter into any of the regression equations.

3.4 DISCUSSION

3.4.1 Muscle Cross-sectional Area

The present study is the first to determine and compare muscle CSA and volume in the quadriceps and hamstring muscle groups, using the multiple slice CT scan technique, and it is the second study that has taken multiple CT scans of limbs in individuals from two widely separated age groups. In an earlier study, Rice et al. (1988) determined the CSA and volume of the elbow flexor and extensor, and plantar flexor muscle groups. Rice et al. showed that muscles in the elderly were smaller (28-36%) even though overall limb size was not different. The amount of NMT within the muscle groups was also greater in the elderly subjects, particularly in the plantar flexor group (81%) (Rice et al.. 1988). The present results extend the findings of Rice et al. to the quadriceps and hamstring muscle groups, and confirm that there are profound changes in limb composition associated with ageing, even in muscles used in normal walking and climbing. The elderly men had significantly smaller muscle plus bone (13.0%), quadriceps compartment (21.8%), quadriceps (26.4%), hamstrings compartment (10.1%) and hamstring (17.9%) cross-sectional areas. Conversely, the skin and subcutaneous fat CSA was increased (37.6%) in the elderly men, as was the CSA of NMT contained within both the quadriceps (59.4%) and hamstring (127.3%) compartments.

Previous imaging studies involving young subjects have determined both total thigh (Borkan et al., 1983; Buckley et al., 1987; Narici et al., 1988) and quadriceps CSA (Termote et al., 1980; Jones et al., 1983; Maughan et al., 1983; Schantz et al., 1983). To date however, only Narici et al. (1988) (using NMR) have reported any data on hamstring CSA.

Data from the young men in the current study for total thigh, muscle plus bone, and quadriceps CSA agree well with previously reported results (Termote et al., 1980; Borkan et al., 1983; Maughan et al., 1983; Narici et al. 1988). In addition, the hamstring CSA reported by Narici et al. (1988) is similar to the values obtained in the present study.

Less comparative data are available for elderly men. Data from imaging techniques have been provided by Borkan et al. (1983), Fiatarone et al. (1990), and Schwartz et al. (1990) for total thigh CSA, and by Frontera et al. (1988), Fiatarone et al. (1990) and Sipila and Suominen (1991a) (using ultra sound) for quadriceps CSA. No previous <u>in vivo</u> study has reported any data on hamstring CSA in elderly men.

The data for quadriceps CSA agrees with that of Frontera et al. (1988), but is greater than the values from Fiatarone et al. (1990) and Sipila and Suominen (1991a). Fiatarone et al. studied an older group (mean age - 90.1 yrs) which may explain the discrepancy between the present study and their results. Sipila and Suominen used ultrasound to determine CSA and have since reported (Sipila and Suominen, 1991b) that CT scans yield larger estimates of quadriceps CSA as compared to ultrasound. The total thigh muscle CSA (muscle plus bone CSA minus bone CSA) is in agreement with the data reported by Schwartz et al. (1990).

3.4.2 Muscle Volumes

In vivo lean thigh volume data for elderly men (55-71 yrs) using anthropometric techniques have been reported by Makrides et al. (1985). Data for young men have been reported by Ingemann-Hansen and Halkjaer-Kristensen (1977) (water displacement) and McCartney et al. (1983) (3.7-5.3 l, CT scans). The values for the elderly men in the present study (3.4 l) were less than those reported by Makrides et al. (4.3 l) but this might be explained by the greater age of the subjects in the present study and the different measurement techniques. Ingemann-Hansen and Halkjaer-Kristensen (1977) studied young male soccer players and this may explain the larger lean thigh volumes reported in their study (4.9 l).

The results for the young men in the present study are similar to the values reported by McCartney et al. (1983).

Cadaver study data for thigh component volumes have been reported by Alexander and Vernon (1975), Wickiewicz et al. (1983) and Friederich and Brand (1990). Rice et al. (1988) have previously described the inherent problems with cadaver study results which must be taken into consideration before comparisons with <u>in vivo</u> results can be made. Briefly, cadaver studies usually involve small numbers of cadavers, or limb sections, and there is usually little information available about pre-death activity or disease states. Ageing, inactivity and/or debilitation are likely to have significant effects on muscle size. Given these limitations of cadaver study data, comparisons with <u>in vivo</u> limb volume results can be made after first converting cadaver muscle masses to volumes using the following formula, V = m x p, where V = volume (cm^3), m = mass (g) and p = density, taken as 1.056 $g \cdot cm^{-2}$ (Mendez and Key, 1960). Quadriceps volume values from the young (1804 cm^3) and elderly (1256 cm^3) men in the present study are similar to those from Friederich and Brand (1990) (1913 cm^3) and Alexander and Vernon (1231 cm^3). The limb section from the study by Friederich and Brand came from a 37 year old man, while the limb from the study by Alexander and Vernon was from a 48 year old man, sedentary due to illness. The hamstring volumes from the young and elderly men in the present study (772 and 648 cm^3, respectively) were also similar to those from Friederich and Brand (876 cm^3) and Alexander and Vernon (517 cm^3). Thus, the multiple slice CT scan technique for determining in vivo limb component volumes appears to yield comparable values to those determined in cadaver studies.

There are some limitations in determining muscle volume using the multiple slice CT scan technique. One of these is the difficulty in separating muscle from tendon, which may comprise a sizeable amount of the total limb volume, at least in the forearm (Cooper et al., 1955). Another problem is the subjectivity involved in determining exact muscle boundaries in lean and/or muscular subjects. Finally, the truncated cone assumption (Jones and Pearson, 1969) used in determining volumes may not hold in all cases as the various thigh components are irregularly shaped. However, comparison of the current data with the available cadaver data indicates that these limitations do not seem to critically affect in vivo volume determinations. As Rice et al. (1988) have suggested, the advantage of determining muscle volume is that it permits calculation of the physiological cross-sectional area (PCSA), a more meaningful measure than anatomical CSA when normalizing force exerted by muscle tissue (Edgerton et al., 1986; Friederich and Brand, 1990).

The multiple slice CT scan procedures used to quantify thigh component volumes in this study are time consuming, expensive and involve an unacceptable ionizing radiation risk for use in large scale studies. However, the regression equations (Table 9) permit, with a reasonable degree of accuracy, the prediction of various thigh component volumes from measures of thigh length and component CSA from a single mid-limb CT scan. These predicted component volumes allow *in vivo* estimates of PCSA which can then be used to more accurately describe relationships between muscle strength and size.

The present study has demonstrated the need to use accurate imaging techniques when determining limb component CSA and volume. CT scans in the elderly men revealed decreases in actual quadriceps and hamstring muscle mass, and increases in subcutaneous fat and in NMT within the muscle compartments, despite no difference in overall thigh girth. Anthropometric techniques are not capable of determining these differences. Evaluating the results of interventions designed to increase muscle strength, or attempting to explain performance based on some measure of actual muscle size or volume cannot be done with any degree of confidence unless accurate information is available regarding limb component composition.

CHAPTER FOUR

KNEE EXTENSOR AND KNEE FLEXOR STRENGTH:CROSS SECTIONAL AREA RATIOS IN YOUNG AND ELDERLY MEN

4.1 INTRODUCTION

The loss of strength associated with ageing is well documented (Grimby and Saltin, 1983; Young et al., 1985; Fisher et al., 1990). Furthermore, the proximal muscles (knee extensors and flexors) of the lower limb appear to be particularly affected by muscle fibre atrophy and consequent loss of strength (Tomonaga, 1977; Larsson et al., 1979). This atrophy may be localized to the type II muscle fibres (Aniansson et al., 1986). Given the importance of the proximal lower limb muscles in every day motor skills and locomotor activities, it is important to determine the effect of ageing on strength loss in these muscle groups.

As ageing is associated with decreases in both size and strength of muscles, one method of assessing the effect of ageing is to examine the relationship between muscle strength and muscle cross-sectional area (CSA). It is well accepted that a linear relationship exists between muscle CSA and muscle strength (Ikai and Fukunaga, 1968). The recent availability of more precise imaging techniques such as computed tomography (CT) and nuclear magnetic resonance (NMR) has improved the accuracy of muscle CSA determination. This is important because less precise techniques may fail to detect changes within muscle associated with ageing (Rice et al., 1988), thus leading to inappropriate conclusions regarding the actual muscle CSA.

Several previous studies have determined the relationship between knee extensor strength and CSA in young men (Maughan et al., 1983, Schantz et al., 1983; Ryushi et al., 1988). However, less information is available on this relationship in elderly subjects and only one previous study has compared young and elderly men with regard to the relationship between knee extensor strength and CSA (Young et al., 1985). Strength:CSA relationships in both knee flexors and knee extensors have not yet been determined in elderly men while only one previous paper (Narici et al., 1988) has assessed these ratios in young men. Thus, the purpose of this study was to determine and then compare the strength:cross-sectional area ratios of knee extensors and knee flexors in young and elderly men.

4.2 METHODS

Subject selection was as described in Chapter One (p.9). Elderly subjects underwent a medical exam to screen those for whom maximal muscle contraction would be contraindicated. All subjects reported their lower extremity to be free from pathology.

4.2.1 Computed Tomography

The procedures for obtaining and analyzing the CT scans and determining the error of measurement in the subjects were as described in Chapter Three (pp.44-47).

4.2.2 Strength Testing

Concentric knee extension and flexion at 0°/s and 120°/s were tested in random order on the Kinetic-Communicator (Kin-Com), a computer controlled, hydraulically driven, isokinetic dynamometer. The Kin-Com was calibrated before each test using its internal software system. Subjects warmed up on an exercise bicycle for five minutes at a light resistance and performed several stretching exercises for the knee extensors and knee flexors before performing any of the strength tests. Subjects were seated with their back against a rigid support with a hip angle of approximately 80° flexion. Stabilizing belts were secured across the pelvis during all tests, and over the distal third of the thigh during knee flexion in order to minimize upward displacement of the knee. The rotational axis of the dynamometer was aligned coaxially with the lateral epicondyle of the knee during contraction efforts. Foam padding was placed under the popliteal fossa in order to minimize discomfort from compression of the tissues against the seat of the Kin-Com, and to achieve a horizontal orientation of the thigh when examined visually during practice contractions. The resistance pad was positioned just above the ankle where it did not restrict dorsiflexion during knee extension or plantar flexion during knee flexion. The length of the resistance arm was recorded for each subject. Subjects grasped the edge of the Kin-Com table during testing and received moderate verbal encouragement. Data were corrected for the effects of gravity on the leg and the resistance pad of the dynamometer.

Isokinetic knee extension and flexion at 120°/s were performed over the range of 100° to 0° knee flexion. Isometric extension and flexion were performed at 60° and 30° of flexion, respectively. Thus four testing conditions were created; knee extension at 0°/s and 120°/s (Ext0, Ext120) and knee flexion at 0°/s and 120°/s (Flx0, Flx120). Subjects were allowed several practice contractions, gradually building in intensity. Each isokinetic test procedure consisted of two maximal contractions separated by a three second rest during which time the investigator repositioned the resistance arm. For the isometric contractions, the resistance arm was allowed to move through a 10° arc at about 10°/s angular velocity until it reached the designated testing angle. This protocol allowed the subject to gradually build up tension. Isometric contractions were performed for five seconds. Three to five test procedures were performed for each isometric and isokinetic testing condition until the subject reported that he had exerted a maximal effort. One to two minutes of rest were allowed between each procedure.

Peak torques and angles of peak torque were determined from each repetition using the Kin-Com Torque vs Angle program (KC772.047). The data from the repetition yielding the highest peak torques were used for analysis. Impact artifacts (characterized by a sharp spike in the torque-angle plot) were eliminated from the torque records. To facilitate comparisons with previous research, peak torques in Newton·metres (Nm) were converted to Newtons (N) by dividing through by the length of the resistance arm (m).

To test for any possible learning effects, a subset of the subjects (n=10) returned to the lab one month later and performed the strength tests a second time. Intra-class correlation coefficients (1,1) were calculated to determine the reliability of these data. The coefficients obtained for the four testing conditions ranged from 0.894 for Flx120 to 0.967 for Ext120.

4.2.3 Statistical Analysis

Strength:CSA ratios were determined for each movement at each testing velocity. Non-directional independent Student's t-tests were used to compare data from the young and elderly men. Pearson product-moment correlation coefficients were determined between selected muscle strength and CSA measures (SPSS/PC, 1984). The maximum probability level denoting statistical significance was 0.05.

4.3 RESULTS

Subject characteristics are listed in Table 10. Cross-sectional area data from the CT scans are presented in Table 11. All measures except the hamstring values were taken from the mid-thigh scan, representing the level of greatest QCSA. The hamstring values were taken from the next distal scan, representing the level of greatest HCSA. The elderly men had significantly greater amounts of non-muscle tissue in both the quadriceps and hamstring muscle compartments.

All subjects completed the strength testing without incident. Original data expressed in units of torque (Nm) are presented in Table 12. The converted data (N) are shown in Table 13. The elderly men were significantly weaker than the young men in both extension and flexion at both angular velocities (Fig. 12) (22 - 32%). There were no differences in the strength:CSA ratios between young and elderly men at Ext0 or Flx0, but the younger subjects had increased ratios at Ext120 and Flx120 (Table 14).

Correlation coefficients between strength and CSA of the knee extensor and knee flexor muscle groups are presented in Table 15. Significant correlations were found for both flexors and extensors at both velocities for the elderly men, but only for the extensors in the young men. All coefficients were significant when the subjects were pooled.

Table 10. Subject characteristics.

	Young (n=13)	Elderly (n=12)	P value
Age (yrs)	24.5 ± 1.5 (19-34)	70.7 ± 1.3 (65-77)	
Height (cm)	173.9 ± 2.3 (158.0-185.6)	173.8 ± 1.6 (165.0-188.0)	0.96
Weight (kg)	70.0 ± 3.0 (55.0-83.7)	77.1 ± 2.8 (63.0-100.0)	0.10
Thigh length (cm)	26.9 ± 0.7 (21.8-30.6)	24.5 ± 0.7 (22.0-29.0)	0.02
Thigh girth (cm)	52.7 ± 1.7 (46.0-68.8)	51.5 ± 1.1 (47.3-62.4)	0.53

Values are means ± SE, and range in brackets.

Thigh girth taken at mid-thigh skinfold location.

P value refers to probability of t-statistic determined from non-directional independent Student's t-test.

Table 11. Cross-sectional areas determined by computed tomography.

Limb component (cm^2)	Young (n=13)	Elderly (n=12)	P value
Quadriceps compartment	88.2 ± 4.0 (68.8-115)	71.1 ± 3.2 (60-94.9)	0.03
NMT in Quadriceps comp.	3.2 ± 0.3 (1.6-5.6)	5.5 ± 0.5 (3.3-9.9)	0.01
Quadriceps muscles	84.7 ± 3.8 (66-111.1)	65.7 ± 3.0 (54.2-85.0)	0.01
Hamstrings compartment	40.7 ± 2.0 (30.6-52.6)	38.3 ± 2.3 (30.6-57.5)	0.44
NMT in Hamstrings comp.	2.2 ± 0.2 (1.3-3.3)	5.2 ± 0.3 (3.6-7.2)	< 0.01
Hamstring muscles	38.5 ± 1.9 (29.3-50.1)	33.1 ± 2.1 (25.6-50.2)	0.07

Values are means ± SE, and range in brackets.

NMT is non-muscle tissue.

P value refers to probability of t-statistic determined from non-directional independent Student's t-test.

Quadriceps measures taken from mid-thigh scan. Hamstring measures taken from the next distal scan.

Table 12. Knee extensor and knee flexor peak torques (Nm) at 0°/s and 120°/s angular velocity.

Test Condition	Young (n=13)	Elderly (n=12)	Difference (%)	P value
Ext120	204 ± 14 (130-284)	138 ± 6 (100-170)	32.4	< 0.01
Ext0	262 ± 17 (159-348)	199 ± 10 (153-272)	24.0	< 0.01
Flx120	103 ± 7 (60-148)	70 ± 4 (50-96)	32.0	< 0.01
Flx0	144 ± 10 (91-211)	109 ± 7 (81-156)	24.3	≤ 0.01

Values are means ± SE, and range in brackets.

Ext is extension, Flx is flexion.

P value refers to probability of t-statistic determined from non-directional independent Student's t-test.

Table 13. Knee extensor and knee flexor strength (N) at 0°/s and 120°/s angular velocity.

Test Condition	Young (n=13)	Elderly (n=12)	Difference (%)	P value
Ext120	638 ± 40 (437-916)	437 ± 21 (323-533)	31.5	< 0.01
Ext0	819 ± 50 (524-1088)	626 ± 28 (494-837)	23.6	< 0.01
Flx120	320 ± 18 (218-452)	222 ± 14 (161-331)	30.6	< 0.01
Flx0	448 ± 28 (289-626)	348 ± 23 (231-514)	22.3	≤ 0.01

Values are means ± SE, and range in brackets.

Ext is extension, Flx is flexion.

P value refers to probability of t-statistic determined from non-directional independent Student's t-test.

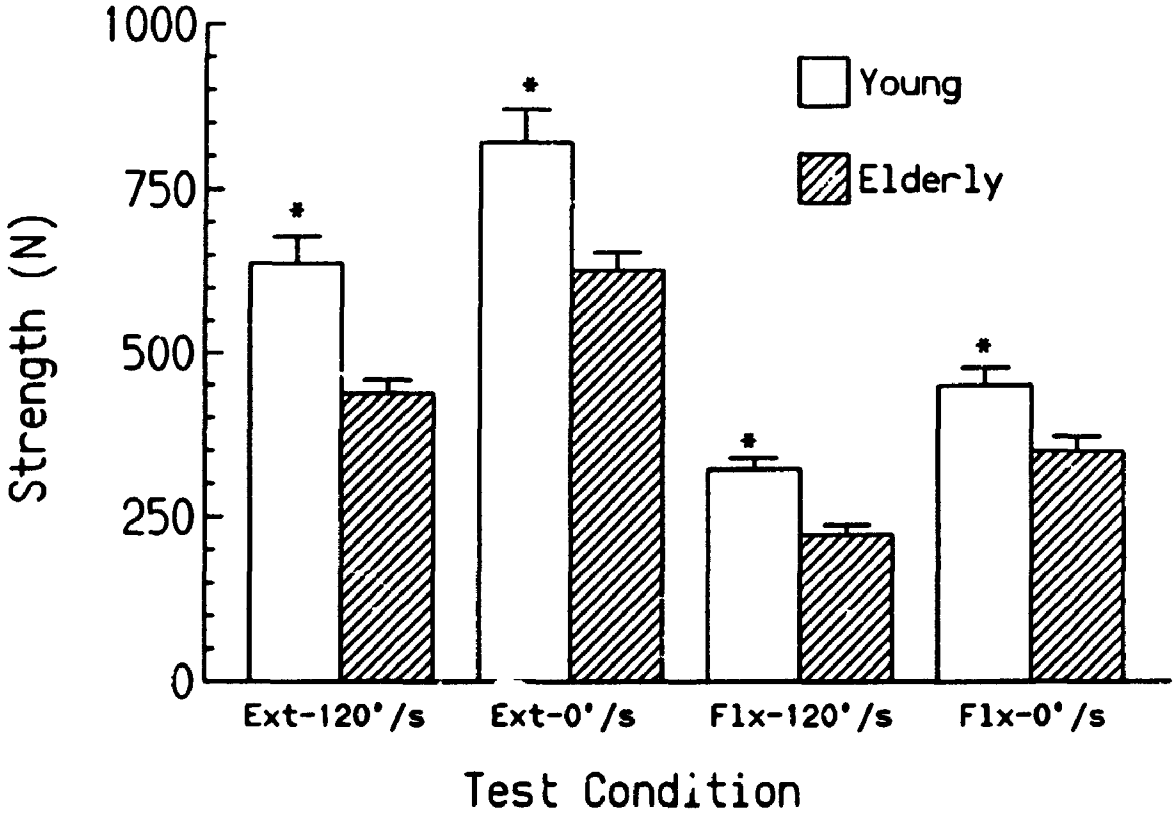


Fig. 12 Knee extensor and knee flexor strength at 0°/s and 120°/s in young and elderly men (means ± SE). * indicates value is significantly greater than elderly group.

Table 14. Strength:cross-sectional area ratios in knee extensors and knee flexors of young and elderly men.

Ratio	Young (n=13)	Elderly (n=12)	P value
Ext120/QCSA	7.47 ± 0.22 (6.09-8.53)	6.71 ± 0.28 (5.48-8.37)	0.05
Ext0/QCSA	9.61 ± 0.37 (7.43-12.22)	9.79 ± 0.35 (7.57-11.40)	0.73
Flx120/HCSA	8.39 ± 0.44 (5.58-11.71)	6.81 ± 0.36 (5.59-8.86)	0.01
Flx0/HCSA	11.72 ± 0.66 (8.55-16.22)	10.62 ± 0.54 (6.86-13.90)	0.21

Units are ($N\,cm^{-2}$).

Values are means ± SE, and range in brackets.

P value refers to probability of t-statistic determined from non-directional independent Student's t-test.

QCSA is quadriceps cross-sectional area from mid-thigh CT scan. HCSA is hamstring cross-sectional area from next distal scan.

Table 15. Correlation coefficients for strength vs cross-sectional area in knee extensor and knee flexor muscle groups at 0°/s and 120°/s in young and elderly men.

Correlation	Young (n=13) r	Young (n=13) P value	Elderly (n=12) r	Elderly (n=12) P value	All (n=25) r	All (n=25) P value
Ext120	0.889	< 0.01	0.623	0.03	0.888	< 0.01
Ext0	0.829	< 0.01	0.667	0.03	0.857	< 0.01
Flx120	0.524	0.07	0.718	< 0.01	0.656	< 0.01
Flx0	0.493	0.09	0.729	< 0.01	0.661	< 0.01

Ext is extension, Flx is flexion.

Area measurement for extension coefficients was quadriceps cross-sectional area from mid-thigh CT scan. Area measurement for flexion coefficients was hamstring cross-sectional area from next distal scan.

P value refers to probability that correlation is due to chance (significance level set at 0.05).

A second correlation between strength and muscle CSA was determined by calculating total strength at each velocity (eg. total strength at 120°/s = sum of Ext120+Flx120) and comparing that to the total quadriceps and hamstring muscle CSA (QHCSA=QCSA+HCSA) (Table 16). Total extension strength (TotExt=Ext120+Ext0) and total flexion strength (TotFlx=Flx120+Flx0) were also correlated against QCSA and HCSA respectively (Table 16). All correlation coefficients were significant for the elderly men while in the young men, only TotFlx vs HCSA did not achieve significance.

Table 16. Correlation coefficients between total strength at each velocity (Tot @ 120, Tot @ 0) and total CSA (QHCSA), and between total extension and total flexion strength (TotExt, TotFlx) and QCSA and HCSA.

	Young (n=13)		Elderly (n=12)		All (n=25)	
Correlation	r	P value	r	P value	r	P value
Tot @ 120	0.863	< 0.01	0.730	< 0.01	0.868	< 0.01
Tot @ 0	0.881	< 0.01	0.808	< 0.01	0.897	< 0.01
TotExt	0.891	< 0.01	0.722	0.01	0.907	< 0.01
TotFlx	0.516	0.07	0.745	< 0.01	0.673	< 0.01

QCSA is quadriceps cross-sectional area from mid-thigh CT scan. HCSA is hamstring cross-sectional area from next distal scan. QHCSA is sum of QCSA and HCSA.

P value refers to probability that correlation is due to chance (significance level set at 0.05).

4.4 DISCUSSION

This is the first study to have determined strength:CSA ratios in knee extensor and knee flexor muscle groups in both young and elderly men. Previous investigators have determined the knee extensor strength:CSA relationship in young and older men (Young et al., 1985), and knee extensor and flexor strength:CSA ratios in young men (Narici et al., 1988). The current results confirm some of the previous findings and provide new information about the effect of ageing on strength:CSA ratios in the knee extensors and knee flexors. There is no age-related difference in the isometric strength:CSA ratio, but the isokinetic ratio is decreased in elderly men, suggesting that their loss of muscle strength is greater than can be accounted for by their decrease in muscle CSA.

4.4.1 Muscle Cross-sectional Area

Accurate determination of strength:CSA ratios depends on precise measurement of both factors in the ratio. A previous study from this laboratory detected significant age-related changes in intra-muscular fat in the elbow extensors and plantar flexors (Rice et al., 1988). Chapter Three of the present study extended these observations to the quadriceps (knee extensors) and hamstrings (knee flexors), thus emphasizing the critical importance of accurate determinations of muscle CSA when comparing young and elderly subjects. The present study has shown that ageing is associated with significant changes in the CSA of muscle and the non-muscle tissue within muscle (Table 11, Figs. 10 and 11). The QCSA measurements of our young and elderly men were similar to previous studies which have also used CT scans (Borkan et al., 1983; Maughan et al., 1983; Frontera et al., 1988). No previous in vivo study has reported data on HCSA in elderly men.

4.4.2 Muscle Strength

Comparison of the strength data in the present study with previous studies is complicated by wide variation in measurement techniques. Data have been collected on both isometric and isokinetic concentric contractions at many joint angles and angular velocities and at several different joint positions. Nevertheless, strength values for both the knee extensors and flexors in our young and elderly subjects fall within ranges established in previous studies (Larsson et al., 1979; Murray et al., 1980; Maughan et al., 1983; Schantz et al., 1983; Young et al., 1985; Jones and Rutherford, 1987; Narici et al., 1988; Borges, 1989). The elderly group was significantly weaker in both flexion and extension at both angular velocities (22-32%). This agrees well with previous data for knee extensor and flexor strength in young and older men reported by Murray et al. (1977, 20-25%), Larsson (1982, 28.6%) and Borges (1989, 27-36%).

The commonly observed decrease in strength with age may be less evident with eccentric contractions (Vandervoort et al., 1990; Poulin et al., 1992). The increased connective tissue associated with ageing was suggested as the reason for this relative maintenance of eccentric strength.

4.4.3 Strength:Cross-sectional Area Ratios

While the precise CSA of the quadriceps and hamstring muscles was measured, it should be recognized that the strength measures for knee extension and knee flexion include contributions from the other thigh and leg muscles which cannot be factored out. It is acknowledged that muscles such as gastrocnemius and gracilis assist in knee flexion. However, in keeping with present practice in the literature, their contributions were not taken into account in the present study. Thus the strength:CSA ratios determined in this study are actually ratios between knee extensor or flexor strength and quadriceps or hamstring CSA. Although these ratios may thus be slightly higher than "pure" muscle strength:CSA ratios, they are as accurate as possible for <u>in vivo</u> testing and permit comparisons with data in the literature.

The young men had significantly greater strength:CSA ratios for both knee flexors and extensors at 120°/s, but there were no age-related differences at 0°/s. Young et al. (1985) have compared knee extensor strength:CSA ratios at 0°/s in young and elderly men. They reported ratios of 8.7 and 7.1

$N\,cm^{-2}$ for young and older men, respectively. These values were significantly different and are also 10-20% smaller than the values obtained in the present study. However, Young et al. measured knee extensor strength at 90° of knee flexion and it has been reported by several investigators that maximal isometric knee extension strength is reached at between 50° and 70° of knee flexion (Murray et al., 1977; Knapik et al., 1983; Colliander and Tesch, 1989). The isometric testing in the present study was conducted at a knee angle of 60° and this may explain why the current knee extensor strength:CSA ratios are higher than those of Young et al. (1985). Jones and Rutherford (1987) also tested untrained young men at 90° of knee flexion and reported a ratio of 7.7 $N\cdot cm^{-2}$.

There were no differences in either knee extensor or knee flexor strength:CSA ratios at 0°/s between the young and elderly men. While no previous study has compared isometric hamstring strength:CSA ratios in elderly men, Young et al. (1985) observed an age-related difference in the knee extensor isometric strength ratio. However, their elderly subjects were on average, five years older than the subjects in the present study, and they were 39% weaker in knee extension than their younger counterparts, compared to a value of 24% in the present study.

Age-related differences in both knee flexor and knee extensor strength:CSA ratios were observed in the present study during the testing at 120°/s. This may be due to preferential atrophy of fast contracting type II muscle fibres in the elderly (Larsson et al., 1979; Grimby and Saltin, 1983). In support of this, Klitgaard et al. (1990) have recently reported a 20-26% drop in velocity at given torques in elderly men which they linked to a relative increase in type I myosin heavy chains. Grindrod et al. (1987) reported a significant positive relationship between force per unit area and the percentage of the area occupied by type II fibres and suggested that the intrinsic strength of type II fibres is 1.8 times that of type I. Previous work from this laboratory has shown that age is a significant determinant of plantar flexion torque at high speeds (180°/s), but not at lower velocities (30°/s) (Cunningham et al., 1987), supporting the suggestion from the present study that there is a relative loss of high speed strength in the elderly.

4.4.4 Variability in Strength:CSA Ratios

McCullagh et al. (1987) suggested that some of the wide variability associated with strength:CSA ratios could be accounted for by biomechanical differences in the lever system. The actual force produced along the quadriceps tendon can be converted to the extensor force produced at the ankle by taking into account the length of the resistance arm and the radius from the centre of rotation of the femoral condyle to the tendon (Smidt, 1973). The tendon force can then be divided by the muscle CSA to yield a tendon stress ratio.

Using the data from Smidt (1973) for the internal knee radii, isometric stress along the quadriceps and hamstring tendons in the young men in the present study was estimated to be 64 and 98 $N cm^{-2}$ respectively (Table 17).

Stress ratios reported in the literature for knee flexors and extensors are presented in Table 17. The CSA values from Wickiewicz et al. (1985) were determined from cadaver limbs and represent the physiological CSA (PCSA) of the muscles. PCSA takes into account the pennation angle of the muscle and is measured perpendicular to each fibre instead of perpendicularly to the muscle as a whole. PCSA is thus considerably larger than anatomical CSA for pennate and bipennate muscles like the quadriceps, and hence will result in lower stress:CSA ratios.

Previous investigators have remarked on the wide variability in strength:CSA ratios (Maughan et al., 1983; Young et al., 1985). There are several sources of variability in addition to the above-mentioned biomechanical factors and angles at which isometric strength is measured. One of these is the muscle groups included in the CSA measurements. Narici et al. (1988) included gracilis and sartorius muscles in their knee flexor CSA; this may explain why their flexor stress ratio in Table 17 is lower. A fourth source of variability is the measuring technique used to determine muscle CSA. Some studies have used ultrasound to measure CSA, and Sipila and Suominen (1991b) have recently reported that CT yields higher

Table 17. Stress ratios and cross-sectional areas of knee extensors and flexors reported in the literature.

Muscle group	CSA cm^2	Stress $N \cdot cm^{-2}$	Reference	Year
Knee extensors	74-110	58-70	Tsunoda et al.	1983
Knee extensors	79.0	86.2	McCullagh et al.	1983
Knee extensors	87.0	42.2	Wickiewicz et al.	1985
Knee extensors	83.9	80.1	Narici et al.	1988
Knee extensors	83.7 (S)	55	Ryushi et al.	1988
Knee extensors	60.9	42	Ryushi et al.	1988
Knee extensors	80.4 (S)	60.8	Hakkinen et al.	1989
Knee extensors	80.1 (Sp)	55.0	Hakkinen et al.	1989
Knee extensors	72.8 (E)	49.3	Hakkinen et al.	1989
Knee extensors	80.1	56	Klitgaard et al.	1990
Knee extensors	60.8 (O)	45	Klitgaard et al.	1990
Knee extensors	71.7 (O,S)	70	Klitgaard et al.	1990
Knee extensors	84.7	64.0	Current study	
Knee extensors	65.7 (O)	64.9	Current study	
Knee flexors	42.0	78.9	Wickiewicz et al.	1985
Knee flexors	43.5	70.5	Narici et al.	1988
Knee flexors	38.5	98.0	Current study	
Knee flexors	33.1 (O)	86.9	Current study	

(S) strength trained, (Sp) sprint, (E) endurance, (O) older men.

estimates of thigh CSA than ultrasound. NMR, such as used by Narici et al. (1988), may be the most accurate of all the available imaging systems, particularly for differentiating closely packed muscle groups. A fifth source is the activity level of the subjects. Sprinters tested by Maughan et al. (1983) had a knee extensor strength:CSA ratio significantly greater than marathon runners, and the data from Hakkinen et al. (1988) and Klitgaard et al. (1990) in Table 17 show similar training state differences. A sixth cause of variability in strength:CSA ratios is the muscle fibre composition, particularly with isokinetic testing at high angular velocities (Maughan, 1984). A final source may arise from psychological factors in that subjects must be well motivated to put forth maximal efforts in strength testing.

4.4.5 Correlations Between Strength and CSA

Both knee flexor and knee extensor strength were significantly related to muscle CSA in the elderly men, but only knee extensor strength correlated significantly in the young men. Interpretation of these results is complex. The younger men may have needed more practice during the flexion tests in order to produce a true maximal effort, although their intra-class correlation coefficients for flexion were high. Alternately, since the P values for the flexion correlations approached significance (Table 15), the addition of a few more young subjects may have resulted in a significant correlation. Correlating total flexion strength against HCSA (Table 16) did not improve the coefficient. A literature search did not reveal any data on correlations between strength and HCSA in either young or elderly men.

Previous investigations have produced equivocal results with regard to significant correlations between knee extensor strength and CSA. Maughan et al. (1983) suggested that higher correlation coefficients are achieved when data from disparate groups of subjects (trained-untrained, male-female, etc.) are pooled, and that data from subject groups with little variability may not achieve significance. Young et al. (1985) reported correlations of 0.77 for their elderly men, but only 0.15 for their young group. Maughan et al. (1983) found a significant correlation (0.58) for untrained men, but not for marathoners or strength athletes in the same study. Schantz et al. (1983) reported a high correlation of 0.94 between knee extensor strength at 30°/s and QCSA, but this figure reflected data pooled from male body builders and male and female physical education students. Correlations for the individual groups were not reported. Reed et al. (1991) have suggested that correlations between strength and CSA in the thigh may be lower because of the multiple muscle groups present, not all of which are involved in knee flexion or extension.

This study has provided new information on knee extensor and flexor strength/CSA ratios in young and elderly men. Within the limitations of the data collection techniques and subject selection in this study, it seems that while elderly men are significantly weaker than their younger counterparts in isometric flexion and extension, this decrease in strength is proportional to decreases in knee flexor and knee extensor CSA. However, elderly men appear to be weaker than younger men in isokinetic flexion and extension and their decrease in strength is greater than can be accounted for by their decrease in muscle CSA. A possible cause of this loss of isokinetic strength is a preferential decrease in number and/or size of type II muscle fibres in elderly men. Direct investigation of muscle morphology will be needed to evaluate this suggestion.

CHAPTER FIVE

DETERMINANTS OF CRITICAL POWER AND ANAEROBIC WORK CAPACITY IN YOUNG AND ELDERLY MEN

5.1 INTRODUCTION

Two parameters of muscle function have been identified (Monod and Scherrer, 1965) which describe A) the maximal rate at which a muscle or muscle group can work without fatiguing (critical power), and B) a finite store of intramuscular energy available only at work rates greater than critical power (anaerobic work capacity). The early work in this area has since been extended to whole body exercise on both the treadmill (Hughson et al., 1984; Housh et al., 1991a) and cycle ergometer (Moritani et al., 1981; Poole et al., 1988). Subsequent research has identified the effects of pedalling rate (Carnevale and Gaesser, 1991), interval training (Gaesser and Wilson, 1988; Poole et al., 1990) and continuous training (Gaesser and Wilson, 1988) on critical power (CP) and anaerobic work capacity (AWC). Other studies have attempted to validate the original hypothesis that CP represents the maximal rate of non-fatiguing work by determining time to fatigue at power outputs approximating CP (Housh et al., 1989; Housh et al., 1991a; Scarborough et al., 1991).

To date, however, little information is available regarding the possible determinants of these two functionally significant variables. The onset of blood lactate accumulation (OBLA) has been significantly related to CP (Housh et al., 1991b) although no relationship was reported for either the heart rate/work load slope (indicative of efficiency of the central system) or the efficiency of electrical activity in the knee extensors (peripheral system). CP was also found to be strongly correlated with the maximal power output reached during an incremental test (Talbert et al., 1991). AWC has been shown to be related to traditional measures of anaerobic capacity (Wingate test) (Nebelsick-Gullett et al., 1988; Jenkins and Quigley, 1991) although this relationship has also been questioned (Vandewalle et al., 1989).

Previous researchers have established relationships between various morphological measures and aerobic performance on treadmills and cycle ergometers. Leg volumes were found to account for 36% of the variance in total work output in a short duration (two minutes), extremely heavy, constant load cycle ergometer test (Katch, 1974). A linear relationship was found to exist between maximal oxygen consumption ($\dot{V}O_2$max) and thigh muscle width (Cotes and Davies, 1969) while a similar relationship was reported between leg muscle-plus-bone volume and cycle ergometer aerobic power output (Davies, 1974).

No previous work has attempted to determine relationships between CP, AWC and muscle size or strength. In addition, no previous work has investigated any effect of ageing on the relationships between CP and AWC and their possible determinants. Ageing has been associated with losses of aerobic power (Buskirk and Hodgson, 1987), knee extensor strength and size (Young et al., 1985), knee extensor endurance (Nakao et al., 1989), and anaerobic power and capacity (Makrides et al., 1985). Thus, ageing may also be hypothesized to have a significant effect on CP and AWC. The purpose of this study was to determine the relationships between CP and AWC, and measures of muscle size, muscle strength and aerobic power in both young and elderly men.

5.2 METHODS

Subject selection was as described in Chapter One (p.9).

5.2.1 Determination of $\dot{V}O_2$max and Ventilation Threshold

Determination of $\dot{V}O_2$max was as described in Chapter Two (pp.13-14). Ventilation threshold ($\dot{V}$eT) was determined as the $\dot{V}O_2$ where the ventilatory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$) and the end-tidal oxygen partial pressure ($PetO_2$) began a steady increase with no corresponding increases in the ventilatory equivalent for carbon dioxide ($\dot{V}E/\dot{V}CO_2$) or the end-tidal carbon dioxide partial pressure ($PetCO_2$) (Whipp, 1987).

5.2.2 Determination of Critical Power and Anaerobic Work Capacity

The procedures for carrying out the constant load tests and subsequent determination of CP and AWC were as described in Chapter Two (pp.14-15).

5.2.3 Computed Tomography

The procedures for obtaining the multiple slice CT scans, calculating the muscle cross-sectional areas and volumes and determining the error of measurement were as described in Chapter Three (pp.44-47).

5.2.4 Strength Testing

The procedures for measuring isometric and isokinetic strength and for determining the reliability of these measures were as described in Chapter Four (pp.63-65). Isokinetic strength was also measured at 180°/s during the strength testing and those results are presented in this chapter.

5.2.5 Statistical Analysis

Non-directional independent Student's t-tests were used to compare data from the young and elderly men. Pearson product-moment correlation coefficients were computed between CP and AWC, and selected aerobic power and muscle CSA, volume and strength measures. Stepwise multiple linear regression was used to determine prediction equations for CP and AWC

(SPSS/PC, 1984). The level of significance for all tests was set at 0.05.

5.3 RESULTS

Descriptive characteristics for the young (n=13) and elderly (n=12) subjects are presented in Table 1 (Chapter Two, p.18).

The mean data for the elderly group from the ramp test and determination of critical power are expressed relative to the means for the young men in Fig. 13. The actual data are presented in Tables 1 and 2 (Chapter Two, pp.18,20).

Typical CT scan images of quadriceps and hamstring muscles in young and elderly men are shown in Fig. 10 and Fig. 11 (Chapter Three, pp.50,51). Data from one elderly subject could not be used for technical reasons. The cross-sectional area and volume measurements are presented in Tables 7 and 8 (Chapter Three, pp.52,53). The elderly men had significantly smaller quadriceps and hamstring CSA, but their non-muscle tissue areas in each compartment were greater. Similar relationships were observed for thigh component volumes.

All subjects completed the strength testing without incident. The elderly men were significantly weaker in both knee extension and flexion at all three angular velocities (Table 18). Their values are expressed relative to the mean values for the young group in Fig. 14.

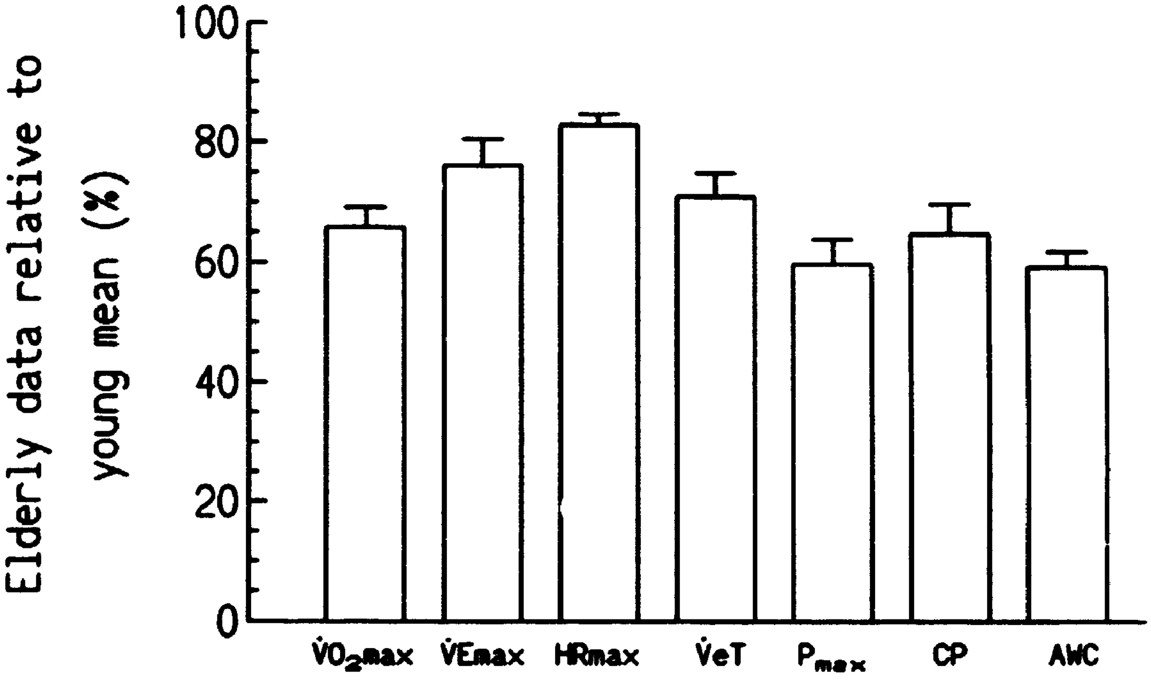


Fig. 13 Ramp test and critical power variables (means ± SE) for the elderly men expressed relative to values for the young men. All values for the elderly men were significantly less than the young men's values.

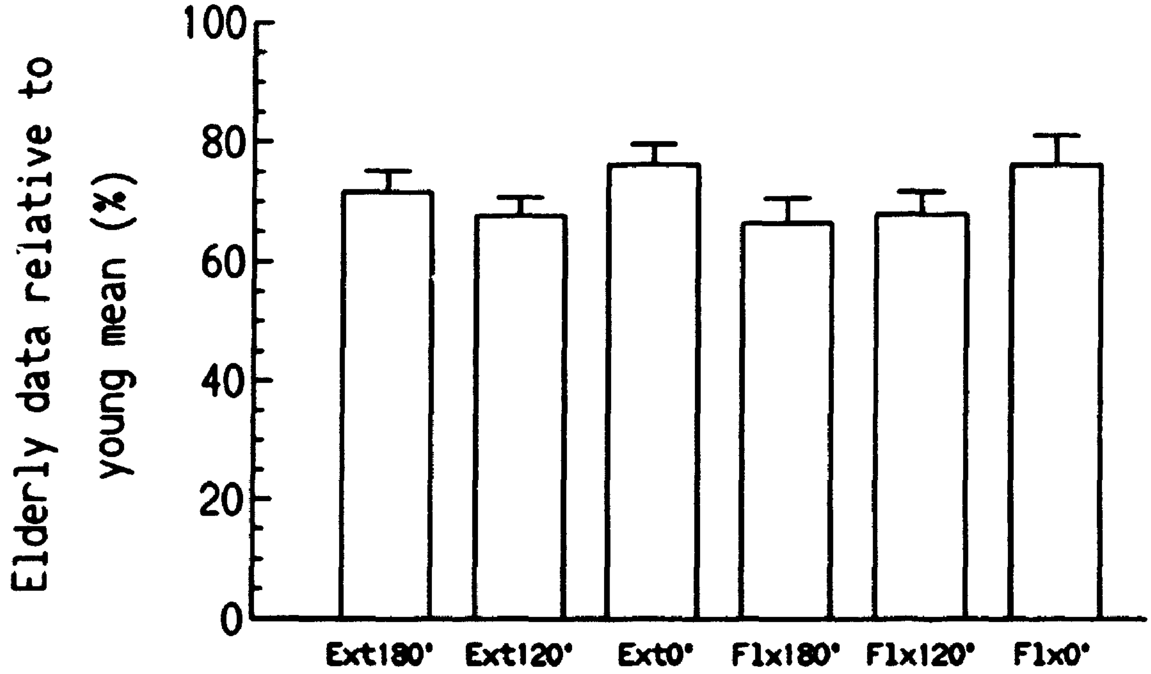


Fig. 14 Peak torques (means ± SE) for knee extensors and knee flexors of elderly men at 180°/s, 120°/s and 0°s expressed relative to values for the young men. All values for the elderly men were significantly less than the young men's values.

Since cycling stresses both knee flexors and extensors during each pedal revolution (Ericson et al., 1986), quadriceps and hamstring CSA, and quadriceps and hamstring volumes were combined to yield two additional variables (QHCSA, QHVOL). Similar combinations were made from the strength results to create variables for total extension (TotExt) and flexion (TotFlx) strength, and total strength at each testing velocity (Tot120, Tot180, Tot0). $\dot{V}O_2$max (Fig. 15) and P_{max} were strongly related to CP in both young and elderly men, as were quadriceps and hamstring muscle volumes (Table 19). Quadriceps CSA had the strongest relationship with AWC in the elderly men. There was no significant relationship between AWC and any of the variables for the young men. The only strength variable to attain a significant relationship in either group was total strength at 0°/s (Tot0) with CP in the elderly men.

The results of the multiple regression analysis on CP and AWC are presented in Tables 20 and 21. In Table 20, CP and AWC were removed from the list of independent variables, while in Table 21, they were included. When all subjects were pooled, P_{max} contributed the majority of the explained variance for both CP and AWC (Table 21). Explained variance was less for AWC than CP regardless whether the subjects were pooled or treated as separate groups. When CP and AWC were included in the list of independent variables (Table 21), P_{max} still contributed the largest share of the explained variance in CP

Table 18. Knee extensor and knee flexor muscle peak torque at 0°/s, 120°/s and 180°/s.

Test Condition	Young (Nm)	Elderly (Nm)	Difference (%)	P value
Ext180	166 ± 12 (102-234)	119 ± 6 (89-152)	28.3	< 0.01
Ext120	204 ± 14 (130-284)	138 ± 6 (100-170)	32.4	< 0.01
Ext0	262 ± 17 (159-348)	199 ± 10 (153-272)	24.0	< 0.01
Flx180	93 ± 8 (50-146)	62 ± 4 (45-90)	33.3	< 0.01
Flx120	103 ± 7 (60-148)	70 ± 4 (50-96)	32.0	< 0.01
Flx0	144 ± 10 (91-211)	109 ± 7 (81-156)	24.3	≤ 0.01

Values are means ± SE, and range in brackets.

Ext is extension, Flx is flexion.

P value refers to probability of t-statistic determined from non-directional independent Student's t-test.

Table 19. Correlation coefficients between critical power and anaerobic work capacity, and age, aerobic power, muscle CSA, muscle volume and muscle strength measures.

Variable	Young		Elderly		All Subjects	
	CP	AWC	CP	AWC	CP	AWC
$\dot{V}O_2max$	.91*	.25	.97*	.36	.95*	.68*
P_{max}	.90*	.55	.99*	.36	.96*	.78*
$\dot{V}eT$	.57*	.23	.81*	.14	.83*	.64*
QCSA	.34	.30	.52	.72*	.63*	.68*
HCSA	.41	.07	.61*	.47	.67*	.45*
QHCSA	.40	.24	.69*	.66*	.71*	.64*
QVOL	.67*	.45	.61*	.56	.83*	.75*
HVOL	.56*	.10	.72*	.43	.77*	.53*
QHVOL	.68*	.35	.68*	.51	.84*	.71*
Tot0	36	.22	.68*	.15	.66*	.55*
Tot120	.24	.39	.52	.27	.63*	.69*
Tot180	.18	.42	.46	.27	.57*	.68*
TotExt	.27	.25	.59	.32	.65*	.60*
TotFlx	.25	.15	.52	.03	.61*	.68*
Age	-.12	-.54	-.69*	-.05	-.71*	-.78*

Q (quadriceps), H (hamstrings), CSA (cross-sectional area), VOL (volume), Tot (total strength at each velocity), Ext (extension), Flx (flexion).

*P < .05

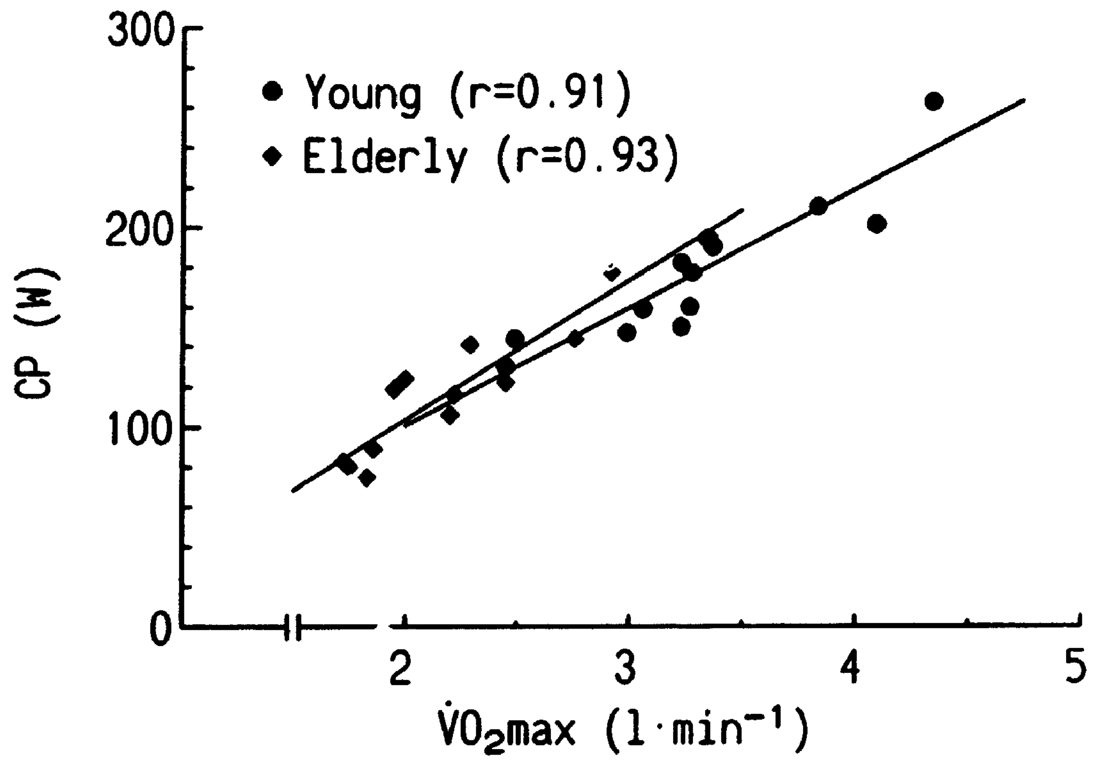


Fig. 15 Correlation between critical power (CP) and maximal oxygen consumption ($\dot{V}O_2max$) in young [CP = 58.69 ($\dot{V}O_2max$) - 16.78, SEE=15.27 W] and elderly [CP = 74.3 ($\dot{V}O_2max$) - 45.88, SEE=12.56 W] men.

and AWC when the subjects were pooled although both AWC and CP contributed significantly to the equations. Age was eliminated as an explanatory variable in this analysis. In general, a greater amount of explained variance resulted from the analysis using CP and AWC as explanatory variables. No variable entered into an equation for AWC in the young men in either Table 20 or 21.

Prediction equations for CP and AWC are presented in Table 22. Since CP and AWC are derived simultaneously and thus cannot be used to predict each other, the equations are derived from the multiple regression analysis in Table 20, where CP and AWC were removed from the list of independent variables.

Table 20. Results of multiple regression analysis for CP and AWC.

Dependent variable	Explanatory variable	P	Incremental % variation explained[*] (R^2)	Overall % variation explained
All subjects:				
CP	P_{max}	< 0.01	92.54	92.54
	$\dot{V}O_2max$	0.02	1.64	94.18
	Tot180	0.01	1.90	96.08
	Age	0.03	0.90	96.98
AWC	P_{max}	< 0.01	60.95	60.95
Young men:				
CP	$\dot{V}O_2max$	< 0.01	82.79	82.79
	P_{max}	0.03	6.46	89.25
	Tot180	0.03	4.53	93.78
AWC	No variable entered into the equation			
Elderly men:				
CP	P_{max}	< 0.01	97.72	97.72
	Age	0.04	0.97	98.69
AWC	QHCSA	0.03	43.35	43.35

P_{max} (maximal power output), Tot180 (total strength knee flexors and extensors at 180°/s), QHCSA (total CSA of quadriceps and hamstrings)

P values refer to significance of the F-statistic of the indicated explanatory variable in the full multiple regression

[*] indicates the increase in percentage of variance explained when the indicated variable is added last.

Table 21. Results of multiple regression analysis on CP and AWC including CP and AWC in the explanatory variable list.

Dependent variable	Explanatory variable	P	Incremental % variation explained* (R^2)	Overall % variation explained
All subjects:				
CP	P_{max}	< 0.01	92.54	92.54
	AWC	< 0.01	4.85	97.39
AWC	P_{max}	< 0.01	60.95	60.95
	CP	< 0.01	25.37	86.31
Young men:				
CP	$\dot{V}O_2max$	< 0.01	82.79	82.79
	P_{max}	0.03	6.46	89.25
	AWC	0.01	5.66	94.91
AWC	No variable entered into the equation			
Elderly men:				
CP	P_{max}	< 0.01	97.72	97.72
	AWC	0.02	1.22	98.94
AWC	QHCSA	0.03	43.35	43.35

P_{max} (maximal power output), QHCSA (total CSA of the quadriceps and hamstrings).

P values refer to significance of the F-statistic of the indicated explanatory variable in the full multiple regression

* indicates the increase in percentage of variance explained when the indicated variable is added last.

Table 22. Prediction equations for CP and AWC from multiple regression analysis in Table 20.

Dependent variable	Explanatory variables	SEE
CP (W):		
- young men	$= 41.21 (\dot{V}O_2max) + 0.32 (P_{max}) - 0.12 (Tot180) - 17.99$	10.15 W (5.7%)
- elderly men	$= 0.66 (P_{max}) - 0.87 (age) + 63.96$	4.05 W (3.6%)
- all subjects	$= 0.42 (P_{max}) + 33.91 (\dot{V}O_2max) - 0.11 (Tot180) + 0.32 (age)$	8.81 W (5.8%)
AWC (kJ)		
- young men	No variables entered into the equation	
- elderly men	$= 0.06 (QHCSA) + 2.53$	0.91 kJ (11.2%)
- all subjects	$= 0.04 (P_{max}) + 1.58$	2.48 kJ (22.5%)

P_{max} (maximal power output), Tot180 (total strength knee flexors and extensors at 180°/s), QHCSA (total CSA of quadriceps and hamstrings). SEE is standard error of estimate.

5.4 DISCUSSION

The purpose of the present study was to identify determinants of CP and AWC. Measures of aerobic power, muscle CSA, volume and strength were studied in addition to age. This is the first attempt to determine relationships between CP and AWC, and muscle size, muscle strength and age. This study has shown that while muscle CSA and volumes are significantly related to CP and AWC, aerobic power measures are better predictors, and that there are age-related differences in these relationships. The present study has also shown that muscle strength as measured in this study has little relationship with either CP or AWC.

The elderly men in the present study were healthy and active, but were not currently involved in endurance type training. Their values for $\dot{V}O_2max$, Vet and relative $\dot{V}eT$ ($\dot{V}eT/\dot{V}O_2max$, 58%) were similar to those obtained from elderly men in previous studies from this laboratory (Cunningham et al., 1985; Thomas et al., 1985).

Critical power in the young men was about 10% less than determined in previous studies of young men (Moritani et al., 1981; Poole et al., 1988), but this difference may be related to the lower $\dot{V}O_2max$ of the young men in the present study (Chapter Two, p.32). AWC values were similar to previously published data (Poole et al., 1988; Housh et al., 1989). CP and AWC have not previously been determined in the elderly, thus there are no data to compare with the values of 115 W and

8.1 kJ obtained in this study. Compared to the young men, the values of the elderly men for $\dot{V}eT$, $\dot{V}O_2max$, CP and AWC were 71, 67, 65 and 58% respectively, suggesting that anaerobic performance of elderly men may decline at a faster rate than aerobic performance. Few previous studies have compared age-related declines in aerobic and anaerobic performance. Grassi et al. (1991) reported that peak anaerobic power in 75 year old master athletes was reduced to about 50% of the value measured in 20 year old men. However, Makrides et al. (1990) have also reported that relative values for anaerobic peak power (67%) and anaerobic capacity (69%) were higher than relative values for $\dot{V}O_2max$ (63%) in comparing elderly (65 y) to young (27 y) men. Further study is needed to evaluate the suggestion raised by the data in the current study.

The multiple slice CT scan technique is an accurate method of determining muscle CSA and muscle volumes (Rice et al., 1988). Quadriceps CSA values for the young and elderly men are in agreement with previously reported results (Maughan et al., 1983; Frontera et al., 1988). Less data are available for hamstring CSA but similar values for young men have been reported (Narici et al., 1988). No previous data are available on hamstring CSA in elderly men.

The only available data on quadriceps and hamstring muscle volumes are from cadaver studies (Alexander and Vernon, 1975; Friederich and Brand, 1990). In comparing cadaver and *in vivo* data, allowances must be made for the limitations inherent in cadaver studies. These include small numbers of limbs or cadavers, possible size changes with preservation and little information about pre-death activity or disease states. However, converting muscle masses from cadaver studies (Alexander and Vernon, 1975; Friederich and Brand, 1990) to muscle volumes yields similar quadriceps and hamstring volumes to those obtained through the multiple slice CT scan technique used in the present study.

Values for knee flexor and extensor isokinetic peak torques in the young and elderly men fall within ranges established in previous studies (Narici et al., 1988; Borges, 1989). The knee flexors and extensors in the elderly men were significantly weaker at all three testing velocities (24-33%). Previous investigators have reported similar degrees of strength loss in these muscle groups in elderly men (Murray et al., 1980; Borges, 1989).

Significant relationships have previously been reported between CP, and both $\dot{V}eT$ and $\dot{V}O_2max$ (Moritani et al., 1981) as well as P_{max} (Talbert et al., 1991) in young men. Strong correlations were found in the current study between CP and $\dot{V}O_2max$, P_{max} and $\dot{V}eT$ in the elderly as well as the young men, suggesting that CP may be determined by the same factors across age. CP is thought to reflect inherent characteristics of the aerobic energy supply system during exercise (Moritani et al., 1981; Whipp et al., 1982; Hughson et al., 1984; Gaesser and Wilson, 1988; Poole et al., 1988). The high percentage of explained variance in CP by $\dot{V}O_2$max (Fig. 15) and lack of correlation between CP and almost all of the strength measures indirectly support this suggestion. More direct support is provided by studies which have shown that CP (like $\dot{V}$eT and $\dot{V}O_2$max) is increased in hyperoxia (Whipp et al., 1982) and decreased in hypoxia (Monod and Scherrer, 1965; Moritani et al., 1981; Whipp et al., 1982). Training studies involving both interval (Gaesser and Wilson, 1988; Poole et al., 1988) and continuous (Gaesser and Wilson, 1988) training have consistently shown that CP is increased by aerobic exercise. However, Housh et al. (1991b) have recently shown that CP was not related to an index of efficiency of central systems (HR/work rate slope), and Gaesser and Wilson (1988) concluded that factors contributing to an increased CP with training are not the same as those contributing to an increased $\dot{V}O_2$max. Thus, the role of central systems as a limiting factor in CP is unclear at present and must await further study.

Critical power may also reflect some degree of anaerobic metabolism as fatigue has been shown to occur in approximately 33 minutes in young men who rode to exhaustion at CP (Housh et al., 1989), and in approximately 18 minutes at CP+5% (Poole et al., 1988). This indicates that CP does not reflect a work rate for which energy is derived from purely aerobic sources. Blood lactate concentrations increased and $PaCO_2$ decreased steadily throughout the 24 minute test used in the current study to evaluate the hypothesis that CP represented the maximal rate of non-fatiguing work (Chapter Two). This would also suggest that exercise at CP requires a significant contribution of energy supplied by the anaerobic system.

Strength seemed to have little relationship to CP in the present study. However, hamstring and quadriceps CSA in elderly men, and hamstring and quadriceps volumes in both young and elderly men were significantly related to CP. These findings confirm the work of Davies (1974) who reported significant correlations between leg muscle-plus-bone volume and aerobic power output, and Cotes and Davies (1969) who found a relationship between thigh muscle width and $\dot{V}O_2$max. Leg volume also accounted for over one-third of the variance in total work output in a short, high intensity, constant load cycle ergometer test (Katch, 1974). The male subjects in these studies ranged between seven and 55 years of age. Thus, the current results suggest that the amount of muscle, measured as muscle CSA or volume, rather than muscle strength, is related to the ability to perform extended exercise at high power outputs without fatigue. However, this suggestion must be interpreted with caution because strength is related to muscle CSA (Ikai and Fukunaga, 1968; Maughan et al., 1983). Marcinik et al. (1991) have recently shown that strength training produced a 33% increase in cycle ergometer endurance time with no corresponding increase in $\dot{V}O_2$max. Strength may thus be expected to have an effect on CP. The suggestion from the current data that muscle size rather than muscle strength is related to high intensity endurance performance may also not hold true for treadmill exercise where work done against gravity is a factor. In support of this, Hickson et al. (1980) have shown that strength training resulted in a significantly greater increase in time to fatigue during cycling (which requires greater leg strength) as compared to running.

It should also be mentioned that correlations between the strength measures and CP were uniformly higher in the elderly men and a significant correlation was obtained between CP and total flexor and extensor strength at 0°/s (Tot0) (Table 19). It may be that leg strength is relatively more important for aerobic performance in elderly men. Fleg and Lakatta (1988) have shown that a large portion of the decrease in $\dot{V}O_2$max with age is explained by the corresponding loss of muscle mass. There also appears to be an age-related difference in the response to strength training. Frontera et al. (1990) showed that strength training increased both strength and aerobic power in elderly men while strength training studies involving young men have shown increases only in strength (Hickson et al., 1980; Rutherford et al., 1986).

There was no significant relationship between AWC and any independent variable in the young men, while in the elderly group, only quadriceps CSA, and the sum of quadriceps and hamstring CSA were related to AWC. Previous studies have consistently shown good correlations between AWC and other measures of anaerobic capacity (Nebelsick-Gullett et al., 1988; Jenkins and Quigley, 1991). Thigh CSA has been correlated with maximal power in the Wingate anaerobic test (Beckett, 1991). Knee extension peak torques at 120°/s and 180°/s have been correlated with both anaerobic power and capacity from the Wingate test (Thorland et al., 1987) while Smith et al. (1987) have shown that isokinetic flexion and extension peak torques at 180°/s are significantly related to Wingate mean power.

Given that isokinetic strength measures are significantly related to anaerobic performance indices from the Wingate test (Smith et al., 1987; Thorland et al., 1987), and that AWC has been significantly related to those same indices (Nebelsick-Gullett et al., 1988, Vandewalle et al., 1989), it was surprising that no significant correlations were observed between the isokinetic strength measures and AWC. A relationship does exist when the subjects are pooled (Table 19), but this reflects the fact that age has a significant effect on AWC ($r = -.78$, $P < 0.01$) as well as on muscle strength.

The exact physiological significance of AWC is difficult to determine. The original hypothesis was that AWC represented a finite store of energy from intramuscular sources (high energy phosphates, anaerobic glycolysis, myoglobin O_2 stores) available only at work rates greater than CP. However, Vandewalle et al. (1989) have questioned the degree to which AWC represents maximal anaerobic capacity, while glycogen depletion studies have shown that glycogen levels do not limit exercise endurance at power loadings above CP (Saltin and Karlsson, 1971). Thus, the criginal theoretical definition of AWC may not hold true. AWC does not explain a large percentage of the variance in anaerobic capacity as determined in the Wingate test (Nebelsick-Gullett et al., 1988; Vandewalle et al., 1989). Nebelsick-Gullett et al. (1988) have suggested that the balance of the variance in anaerobic capacity may be explained by the relatively high aerobic component of the Wingate test (Serresse et al., 1988). Moritani et al. (1981) reported a strong correlation between $\dot{V}O_2max$ and the sum of CP and AWC (theoretically representing the maximal work capacity). Bulbulian et al. (1986) evaluated determinants of cross-country running performance (time) and found that AWC accounted for 58% of the total explained variance with $\dot{V}O_2max$ and $\dot{V}eT$ accounting for an additional 17%. AWC may thus be related to both aerobic and anaerobic factors. This suggestion is supported by the fact that muscle CSA, the only factor which was related to AWC in elderly men, was also significantly related to CP.

Prediction equations for CP in Table 22 indicate that although a high percentage of the variance can be accounted for by the independent variables, the standard errors may be too large for accurate prediction of CP. Time to fatigue appears to be very sensitive to small variations of power output above and below CP (Fig. 9, p.39). Exercise power outputs of CP+5% result in earlier fatigue characterized by progressive increases in $\dot{V}O_2$, $\dot{V}E$ and blood lactate as compared with exercise at CP (Poole et al., 1988). Exercise at CP predicted from the multiple regression equations may thus require a different intensity than exercise at CP derived directly from a series of constant load tests. Similarly, the standard errors for AWC are also too large for accurate predictions. AWC has previously been found to be less reliable and more variable than CP (Moritani et al., 1981; Gaesser and Wilson, 1988; Poole et al., 1988).

In summary, this study has identified aerobic power, muscle CSA and muscle volume measures which are significantly related to CP and AWC in young and elderly men. This study has also shown that ageing, within the limitations of the study design, may affect both CP and AWC, and that isokinetic or isometric strength has no relationship to AWC in either group of men and only a minor relationship with CP in elderly men. The results suggest that CP is determined primarily by parameters of the aerobic energy system. However, further study is required to clarify the physiological significance of both CP and AWC.

CHAPTER SIX

GENERAL SUMMARY AND IMPLICATIONS

6.1 GENERAL

The purposes of the first study were to determine if CP and AWC could be derived in elderly men, and to determine if CP represented a true rate of non-fatiguing work. The results of the study indicated that CP and AWC can be determined in elderly men with approximately the same level of precision as for young men. In the constant load tests, the elderly men seemed equally capable of putting forth the consistent maximal efforts which are necessary for accurate determination of CP and AWC. CP and AWC were reduced in the elderly men by approximately the same amount as $\dot{V}O_2$max.

Prolonged exercise at CP required a greater percentage of $\dot{V}O_2$max in the elderly men. This may be due to problems in accurately determining a true $\dot{V}O_2$max, or it may reflect an ability of the elderly to work at greater relative work rates. Further studies involving determination of $\dot{V}O_2$max over a series of tests, and comparison of physiological responses during prolonged work at various percentages of $\dot{V}O_2$max are needed to resolve this question.

The temporal profiles of $\dot{V}O_2$, $\dot{V}E$, HR, RER, RPE, blood lactate and $PaCO_2$ monitored during the 24 minute test suggest that CP does not represent a true non-fatiguing work rate, thus failing to confirm the original hypothesis for the concept. Examination of the temporal profiles for the elderly men suggested that their responses to prolonged exercise are less pronounced than the responses of the young men, and that the elderly men were closer to working at a steady state. This is interesting in view of the finding that exercise at CP elicited a higher relative $\dot{V}O_2$ in the elderly men. To help resolve the question of the nature of work rate represented by CP, further studies involving tests to fatigue at CP and at power outputs above and below CP should be performed. In addition, while aerobic training of both the continuous and interval type has been shown to increase CP with no change to AWC (Gaesser and Wilson, 1988; Poole et al., 1990), no study has yet investigated the effects of strength or anaerobic training on CP and AWC.

The purpose of the second study was to determine thigh component CSA and volumes in young and elderly men. The results extend previous findings from the leg and upper arm indicating that older men exhibit pronounced increases in subcutaneous fat and non-muscle tissue within the muscle (Rice et al., 1988). This results in significantly less muscle tissue measured as muscle CSA or estimated as muscle volume. In the current study, both quadriceps and hamstring muscle CSA and muscle volume were significantly decreased in the elderly men even though mid-thigh girth between the two groups was similar, thus re-emphasizing the need for accurate imaging techniques when comparing subjects in widely separated age groups. Regression equations developed from thigh length and CSA from a single CT scan indicated that thigh component volumes can be predicted with a good degree of accuracy. Further study in this area should include direct comparisons of CSA and volumes estimated by both CT and anthropometry to determine the actual degree of difference between the two techniques. A study comparing muscle volumes determined by both CT and cadaver analysis, would also be valuable in determining the validity of the multiple slice CT scan technique.

The third study examined differences in isometric and isokinetic knee extensor and knee flexor strength between young and elderly men. The elderly men were weaker in both flexion and extension at both 0°/s and 120°/s. In the elderly men, strength (both flexion and extension) was significantly related to muscle CSA while only extensor strength was related to muscle CSA in the young men. Knee extensor and flexor strength:CSA ratios were similar between the young and elderly men at 0°/s, but the elderly men had a decreased ratio for both muscle groups at 120°/s suggesting that their decrease in strength at this velocity was greater than could be accounted for by their decrease in muscle strength. This relative loss of high speed strength may be due to decreases in the area and/or number of type II muscle fibres. Further studies involving direct determination of fibre area and fibre number are necessary to evaluate this suggestion. In addition, strength comparisons should be made at greater angular velocities, and eccentric muscle strength should be measured to determine if the results from concentric and isometric exercise in elderly men can be extended to eccentric work.

The fourth study identified determinants of CP and AWC from the various cardiorespiratory, muscle CSA, muscle volume and muscle strength measures determined in the previous studies. The results indicated that CP is most strongly related to measures of aerobic power, although significant relationships were also identified between CP and muscle CSA and muscle volume (Table 19). Only a minor association was found between muscle strength and CP. No variable was related to AWC in the young men, while only a measure of muscle CSA was related to AWC in the elderly men. A significant age effect was found for both CP and AWC when all subjects were pooled. Multiple regression analysis revealed that CP and AWC could be predicted, but the standard errors of estimate (SEE) of the equations were unacceptably large. This study has identified several determinants of CP but further study is required to clarify the physiological significance of both CP and AWC.

Within the limitations of the experimental design and subject selection procedures of this thesis, the results of the present studies suggest that age may have an effect on CP and AWC, isokinetic and isometric strength of both the knee extensors and knee flexors, and cross-sectional area and muscle volume of the quadriceps and hamstring muscle groups. However, age does not seem to affect isometric strength:CSA ratios for either the knee extensors or knee flexors, or the ability of elderly men to perform high intensity exercise for extended durations.

6.2 RECOMMENDATIONS FOR FUTURE STUDY

1. Compare cardiorespiratory and metabolic responses of young and elderly men to prolonged work at various percentages of $\dot{V}O_2max$ to evaluate the suggestion that elderly men are capable of prolonged exercise at greater relative work rates compared to younger men.
2. Determine cardiorespiratory and metabolic responses during exercise to fatigue at power outputs above and below CP to evaluate the nature of the work rate represented by CP.
3. Determine the effects of strength or anaerobic training on CP and AWC.
4. Compare quadriceps and hamstring muscle CSA and volumes estimated by both CT and anthropometry to determine the degree of difference between the two techniques.
5. Compare muscle volumes determined by both CT and cadaver analysis to determine the validity of the multiple slice CT scan technique.
6. Determine muscle fibre area and number across age to evaluate the suggestion that there is an age related

preferential loss in the area and/or number in type II muscle fibres.

7. Determine if the strength:CSA ratio results from isometric and concentric exercise in elderly men can be extended to eccentric work.

8. Identify potential cardiorespiratory and cardiovascular determinants to clarify the physiological significance of CP.

9. Identify potential determinants of AWC (oxygen debt, anaerobic power and capacity, lactate production and removal rates, constant velocity force production) to clarify its physiological significance.

APPENDIX I

GLOSSARY OF VARIABLES AND UNITS

AWC - anaerobic work capacity, a theoretical finite store of energy from intramuscular sources, available at work rates greater than CP [(derived as Watt minutes, then converted and expressed in kilojoules, (kJ)]

BNA - bone (femur) cross-sectional area (all cross-sectional areas are measured in cm^2)

BNVOL - bone (femur) volume (all volumes are measured in cm^3)

CP - critical power, a theoretical maximal rate of non-fatiguing work (Watts)

CSA - cross-sectional area (cm^2)

CT - computed tomography, an ionizing radiation imaging system

Ext0 - knee extensor strength at 0°/s (Nm)

Ext120 - knee extensor strength at 120°/s (Nm)

Ext180 - knee extensor strength at 180°/s (Nm)

Flx0 - knee flexor strength at 0°/s (Nm)

Flx120 - knee flexor strength at 120°/s (Nm)

Flx180 - knee flexor strength at 180°/s (Nm)

HCCSA - hamstring compartment cross-sectional area

HCSA - hamstring cross-sectional area

HR - heart rate (b$\cdot$min^{-1})

HSCVOL - hamstrings compartment volume

HSVOL - hamstring volume

HU - Hounsfield unit, a measure of density on a CT scan

$[K^+]$ - venous plasma potassium concentration ($mmol \cdot l^{-1}$)

[La] - venous blood lactate concentration ($mmol \cdot l^{-1}$)

MBA - muscle plus bone cross-sectional area

MBVOL - muscle plus bone volume

N - Newtons

Nm - Newton metres

NMR - nuclear magnetic resonance, an imaging system utilizing molecular resonance

NMT - non-muscle tissue (fat, connective tissue, nerves and vascular structures)

$PaCO_2$ - arterial pressure of carbon dioxide (kPa)

PCSA - physiological cross-sectional area (muscle CSA measured at right angles to each muscle fibre)

$PetCO_2$ - end-tidal partial pressure of carbon dioxide (kPa)

$PetO_2$ - end-tidal partial pressure of oxygen (kPa)

P_{max} - maximal power output in an exercise test (Watts)

QCCSA - quadriceps compartment cross-sectional area

QCSA - quadriceps cross-sectional area

QDCVOL - quadriceps compartment volume

QDVOL - quadriceps volume

QHCSA - total cross-sectional area of quadriceps and hamstrings

QHVOL - total volume of quadriceps and hamstrings

RER - respiratory exchange ratio ($\dot{V}CO_2/\dot{V}O_2$)

RPE - rating of perceived exertion (10 point scale)

SSCFA - subcutaneous fat cross-sectional area

SSCFVOL - subcutaneous fat volume

t_f - time measured from onset of work rate to inability to maintain power output (min)

t_{lim} - time to onset of local fatigue at a given power output (min)

Tot0 - total strength at 0°/s (sum of Ext0 and Flx0) (Nm)

Tot120 - total strength at 120°/s (sum of Ext120 and Flx120) (Nm)

Tot180 - total strength at 180°/s (sum of Ext180 and Flx180) (Nm)

TotExt - total knee extensor strength (sum of Ext0, Ext120 and Ext180) (Nm)

TotFlx - total knee flexor strength (sum of Flx0, Flx120 Flx180) (Nm)

TTA - total thigh cross-sectional area

TTVOL - total thigh volume

$\dot{V}E/\dot{V}CO_2$ - ventilatory quotient for carbon dioxide

$\dot{V}E/\dot{V}O_2$ - ventilatory quotient for oxygen

$\dot{V}E$ - expired ventilation ($l \cdot min^{-1}$)

$\dot{V}O_2$ - oxygen consumption ($l \cdot min^{-1}$)

$\dot{V}O_2max$ - maximal oxygen consumption ($l \cdot min^{-1}$)

Wk_{tot} - amount of work performed at a given power output until exhaustion [Wk_{tot}=power(W)xt_f(min)] (Watt minutes)

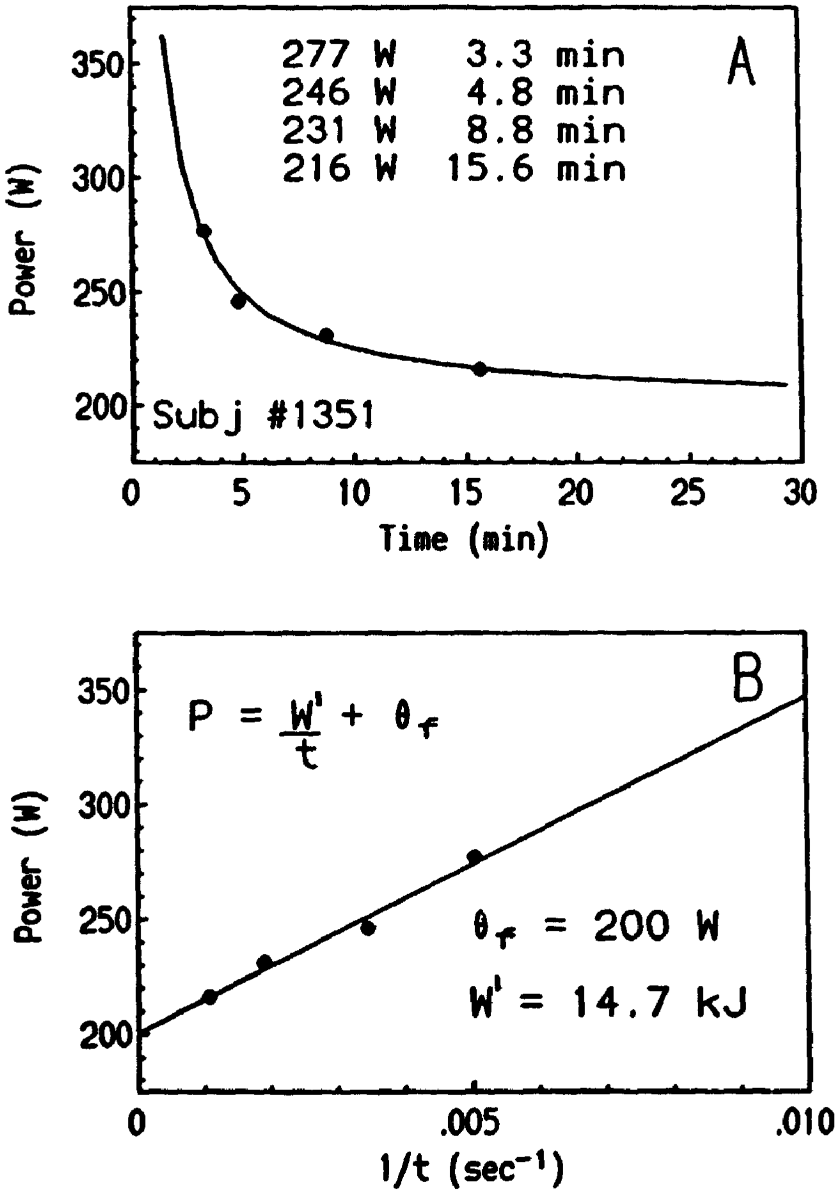
W_{lim} - amount of work performed during a dynamic task until the onset of local exhaustion

W' - constant amount of work normally performed above the fatigue threshold and analogous to AWC (kilojoules, kJ)

θ_f - threshold of fatiguing work, analogous to CP (Watts)

APPENDIX II

DETERMINATION OF θ_f AND W' (Whipp et al., 1982)



A. Relationship between power output (P) and time to fatigue (t).

B. P-t relationship linearized by plotting P against the inverse of time (1/t). θ_f is derived as the y-intercept and W' as the slope of the line.

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