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ORIGINAL ARTICLE

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The effect of ageing in spinal cord injured humans on the blood pressure and heart rate responses during fatiguing isometric exercise

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Abstract Groups of 50 healthy male controls and 50 subjects suffering from paraplegia (aged 20–65 years) were examined as to the inter-relationships between age, paraplegia and the strength, endurance, blood pressure and heart rate responses to fatiguing isometric exercise. Contractions were maintained in both groups under voluntary effort and through a contraction induced by electrical stimulation in the paraplegic group. All contractions were maintained to fatigue at a tension of 40% of the maximal muscle strength in either the handgrip or quadriceps muscles. Muscle strength of the handgrip was higher in the paraplegic subjects than in the controls, averaging 589 N and 463 N, respectively for the two groups. In contrast, quadriceps leg extension strength averaged 696 N in the controls and 190 N in the paraplegic groups; for both groups, ageing was associated with a reduction in muscle strength. While leg endurance was less in the paraplegic group than the control group, handgrip endurance was similar in the two groups, endurance increasing with ageing in both the controls and paraplegics. Both systolic and diastolic blood pressures increased at rest in paraplegic and control subjects with age. The magnitude of the pressor response to exercise also increased with age. This was true during both voluntary exercise and exercise induced through electrical stimulation in the paraplegic groups. The heart rate response (change in heart rate during exercise) to a fatiguing isometric handgrip contraction decreased by about 50% between the ages of 20 and 60 years in both the controls and paraplegics for isometric handgrip exercise. In contrast, heart rate changed little with age during contractions of the quadriceps muscle in paraplegics which were induced by electrical stimulation.

Keywords Isometric · Endurance · Paraplegia · Pressor response to ageing · Paralysis

Introduction

Isometric exercise offers a different type of challenge to the cardiovascular system than does dynamic exercise. While dynamic exercise can be maintained for hours if the anaerobic threshold is not exceeded, isometric contractions maintained at as little as 20% of an individual's maximal strength can only be maintained for minutes (Petrofsky 1982). For example, a contraction at a tension of 40% of an individual's maximal strength can only be maintained for about 2.5 min in the average person (Rohmert 1965; Funderburk et al. 1974). During this period, blood pressure may increase by 50% or more while heart rate increases only modestly (McClosky and Mitchell 1972; Lind et al. 1966; Lind and McNichol 1967). These figures are not absolute, for as we age, our strength decreases, our endurance for fatiguing isometric exercise increases as does the blood pressure during those fatiguing contractions (both systolic and diastolic) (Petrofsky and Lind 1975a, b). Heart rate, on the contrary, decreases during isometric exercise with ageing (Petrofsky and Lind 1975a, b). While these responses to ageing have been documented in both men and women, the effect of ageing on these responses in individuals suffering from a spinal cord injury has not been documented. This may be particularly important since individuals suffering from a spinal cord injury demonstrate a pressor response to isometric exercise even during electrical stimulation of their muscles (Hendershot et al. 1985; Petrofsky and Laymon 2001; Williams 1989; Yamamoto et al. 1999). Electrical

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stimulation is of interest since it is a common type of therapy, both at home and in the clinical setting, given to individuals suffering from paralysis. The pressor responses to both isometric and dynamic exercise are mediated through the sympathetic nervous system (Petrofsky 1982). In individuals having spinal cord injuries, the autonomic outflow from the spinal cord is damaged (Normell and Wallin 1974; Stone et al. 1990). Therefore, the cardiovascular responses of paraplegic patients during exercise may or may not be influenced by ageing as compared to controls. Further, if there is an enhanced response of the cardiovascular system to ageing, it may put patients at more risk during therapy if there is a high isometric component to dynamic exercise such as is found in slow lifting of weights (Petrofsky et al. 1975). This study was conducted to examine the effects of ageing and spinal cord injury on isometric strength, endurance, and the blood pressure and heart rate responses to exercise. Two muscle groups were tested in paraplegic patients; the handgrip muscles where exercise was accomplished under volitional control and the quadriceps muscles where the exercise was elicited by electrical stimulation. For upper body exercise, the response was mediated above the spinal cord injury and for lower body exercise, where the exercise could be induced by electrical stimulation, the cardiovascular responses would have been mediated through lower spinal cord reflexes alone.

Methods

Subjects

The subjects in these studies were divided into two groups as shown in Table 1. Individuals not having any paralysis were the controls (total number = 50). The experimental group consisted of 50 paraplegics having injuries that were diagnosed as complete at the fourth thoracic vertebrae. All subjects were subdivided into four groups showing age ranges of 20–30, 31–40, 41–50 and 51–65 years for both the controls and the paraplegic groups. (see Table 1).

The paraplegic subjects were all between 3 and 10 years post injury. Neither group of subjects had been involved in any type of training program for at least 1 year before the start of these studies.

Since there may be an effect of body fat on isometric endurance, isometric strength and the blood pressure and heart rate response to isometric exercise (Petrofsky and Lind 1975b), both the controls and the paraplegic group were matched for body mass. Table 1 shows the average body mass in each of the age groups for the controls and the experimental groups. The average mass of the control group was 83.5 kg while that of the paraplegic group was 81.2 kg.

In a similar manner, the heights of the groups were also closely matched. The average height of both the group of controls and of the group of paraplegic patients was 183 cm. The heights of the individual age groups are listed in Table 1.

All subjects were told of the purpose of the experiments and of the risks involved. The Committee on Human Experimentation approved all protocols. All subjects signed a statement of informed consent. All subjects were medically screened, so that aside from the paraplegia in the experimental groups, no other medical problems were present. In particular, all paraplegic subjects were screened to exclude those with active bladder infections, which might have triggered the autonomic nervous system to an adverse response during the exercise. To screen for bladder infections, a urine sample was taken 2 days prior to the experiment and urinalysis was performed. If the subjects were non-febrile and the bacteria count in the urine was less than $5{,}000 \cdot \mathrm{mm}^{-3}$, they were deemed to be free of an active infection.

Measurement of strength and endurance

Isometric strength and endurance were measured for each of the subjects using either a portable handgrip dynamometer or a leg dynamometer. The isometric handgrip instrument was a strain-gage type of dynamometer which was made of an aluminum C frame with an adjustable palm bar. As the subjects tried to contract their handgrip muscles, force was applied to a stainless steel bar. The small bend in the bar was transduced to an electrical output by four strain-gages mounted on both sides of the bar. The output was displayed on a Weston 1971 panel meter which was viewed by the subject. The bend in the bar was less than 1×10^{-5} m. A complete description of the handgrip dynamometer has been given elsewhere. (Clarke et al. 1958) For each subject, the hand tested was the predominant hand.

The leg extension strength of the subjects and endurance were also measured using an isometric strain-gage transducer. All subjects sat in a chair with the leg held dependant. A strap was placed 1 cm above the ankle. The strap was connected to an isometric strain-gage transducer so that extension of the leg through either voluntary contraction of the quadriceps muscle or contraction elicited by electrical stimulation would cause the stainless steel bar to bend. This provided an electrical output from the Wheatstone Bridge comprised of four strain-gages mounted on the bar. The output of the bridge was displayed on a Weston 1971 panel meter for the subject and investigators to see. A complete description of the dynamometer has been given elsewhere. (Petrofsky et al. 1975, 2000) The right leg was chosen for examination in the paraplegic group while in the control group the predominant leg was used.

Blood pressure

Systolic and diastolic blood pressures were measured by auscultation of the inactive arm during arm exercise and of the same arm during leg exercise. On each day blood pressure was measured twice at rest and then as quickly as possibly during the fatiguing isometric contraction. In practice, the pressure was measured about

Table 1 General characteristics of the subjects

Group	Ranges of age (years)				
	20–30	31–40	41–50	51–65	Whole group
Control (*n*)	15	10	12	13	50
Paraplegic (*n*)	14	11	13	12	50
Control – body mass (kg)	81.8	83.4	83.5	85.1	83.5
Paraplegic – body mass (kg)	79.1	78.4	82.4	85.0	81.2
Control – height (cm)_	184	185	183	182	183
Paraplegic – height (cm)	181	185	183	184	183

every 20 s. For a contraction which lasted about 2.5 min, about eight blood pressure measurements were made. The blood pressure was then measured at 30 and 60 s post exercise. A linear regression (least squares method) was used to determine the blood pressures at 0%, 20%, 40%, 60%, 80% and 100% of the duration of the contractions. In this way, the normalized pressures could be directly compared from one subject to the other.

Heart rate

Heart rate was measured over 15 s from a continuous record of an electrocardiogram at rest, and at 20%, 40%, 60%, 80% and 100% of the duration of the contractions.

Statistical analysis

Calculation of means, standard deviations, analysis of variance, and Student's *t*-tests was accomplished using an IBM Pentium II computer and a custom statistical package written in Visual Basic 5.0. The level of significance was chosen at $P < 0.05$.

Procedures

Training

For the subjects suffering from paralysis, a period of pre training was employed to strengthen muscles weakened by the paralysis. Isokinetic contractions were exerted through electrical stimulation for 15 training sessions. Subjects accomplished the lifting of weights over a 30 min period 3 days a week. Exercise consisted of using sequential electrical stimulation to elicit contractions of the quadriceps muscle (stimulation with balanced biphasic sine wave, 300 μs pulse width and frequency = 30 Hz) from the 90 °dependant position of the leg through 80° of extension. Training consisted of a 3 s extension followed by 3 s of flexion and 6 s of rest, repeated for 30 min. Initially exercise was against a 2 kg load applied to the ankle. On each day, if the subject could complete the 30 min regime, another kilogram was added on the next day. This allowed the muscles to regain strength during the 5 week training period prior to the experiment period. In practice, in patients suffering complete paraplegia, the leg extension strength rarely exceeded 2 kg prior to training.

For voluntary contractions, training consisted of a session each day for 2 weeks. On each day, subjects would exert a series of three maximal efforts as described above. Then 10 min later, they would exert a fatiguing contraction using their arm or leg muscles. Both muscles were trained in the control subjects on a given day. The subjects were exhorted to maintain their efforts to fatigue. The training was considered complete when the coefficient of variation in isometric endurance from day to day (standard deviation/mean×100) was less than 5%.

To train for isometric contractions using electrical stimulation, the same protocol was used as for the voluntary contractions described above, the difference being that electrical stimulation was used to maintain the 40% contraction to fatigue. The duration of the training was set at 2 weeks after the isokinetic training was complete.

Collection of experiment data

Each subject was examined on four occasions. On each occasion, each subject came into the laboratory and rested in a comfortable environment (18° C) for 30 min. Each subject participated in two different experiments; one in which he exerted a fatiguing isometric contraction of the handgrip muscles and one in which the contraction was exerted either voluntarily (controls) or following electrical stimulation of the quadriceps muscles. Each experiment was replicated on each subject allowing for a total of four experiment sessions.

Isometric handgrip contractions

Each subject sat in a chair with the arm held dependant. The angle of the elbow was kept at 90° and the dynamometer was held in the hand. After an initial rest, each subject was asked to exert a series of three maximal voluntary contractions (MVC, each 2–3 s maximal duration); 2 min was allowed between the contractions. The highest of these contractions was considered the maximal strength of the subjects. Then 10 min later, each subject was asked to maintain a contraction at 40% of their maximal strength until the achievement diminished by 10% irrespective of the subject applying a maximal effort. Blood pressure and heart rate were measured before, during and after the exercise as described above.

Isometric leg contractions

For the control subjects, all contractions of the quadriceps muscles were accomplished through voluntary effort in a manner similar to that described for the handgrip muscles above. The subjects sat in a chair with the leg dependant and elevated above the ground due to the height of the chair. The knee was kept at an angle of 90°. After the rest, the maximal strength was determined from a series of three MVC; each MVC was of 2–3 s duration and 5 min was allowed between contractions. Then 10 min later, each subject was asked to maintain a contraction at 40% of their maximal strength until the achievement dropped by 10% irrespective of the subject applying a maximal effort.

For the subjects suffering paralysis, electrical stimulation was used to elicit contractions of the quadriceps muscle to measure the maximal strength and maintain the isometric contraction to fatigue at 40% of the maximal muscle strength. While the protocol for measuring strength and endurance was the same in the leg muscles of the paraplegic patients as was the case for the voluntary effort of the handgrip muscles, the control of muscle movement in the leg muscles in the paraplegic patients was accomplished using electrical stimulation with a sine-wave sequential powered muscle stimulator. (Challenge 2010a, Maximum Performance Technologies, Redlands, Calif.) The waveform was a balanced biphasic sine wave at a frequency of 30 Hz and a pulse width of 300 μs. The stimulation was applied through three electrodes, a common and two active electrodes placed diagonally across the muscle. The central electrode (common) was applied to the center of the quadriceps muscle over the belly and the other two electrodes were applied 3 cm from the common electrode but diagonally across the muscle. Each pair of electrodes supplied a wave at a frequency of 30 Hz but 180° out of phase with the other electrode. The amplitude was adjusted to be as high as 120 mA root mean square amplitude to achieve the maximal effort or hold the contraction at 40% of the muscle's maximal strength. In practice, with sequential electrical stimulation, full contraction of the muscle could be achieved using no more than 100 mA. Blood pressure and heart rate were measured as described above.

All experiments with the handgrip and leg muscles were repeated on two occasions and on separate days. The order of presentation of the experiments was random. At least 48 h were allowed between each experiment. If a subject did not participate in all four experiments, his data was not included in the data pool.

Results

Table 2 lists the average strength and endurance of the subjects when divided into groups by age. The average strength of the handgrip muscles in the control group was 463 N while that of the paraplegic group was significantly higher at 589 N. For the control subjects, there was a reduction in strength of their handgrip muscles associated with ageing. The loss in strength from age 20–60 years was statistically significant

Table 2 Strength (in newtons) and endurance (in seconds) of subjects [mean (SD)]

Group	Ranges of age (years)				
	20–30	31–40	41–50	51–65	average
Control – hand strength	483 (69)	491 (80)	455 (68)	422 (51)	462
Paraplegic – hand strength	573 (45)	619 (72)	609 (63)	563 (74)	591
Control – hand endurance	135 (13)	139 (12)	144 (11)	151 (14)	142
Paraplegic – hand endurance	137 (14)	141 (13)	143 (14)	148 (11)	142
Control – leg strength	736 (71)	727 (63)	688 (31)	642 (48)	698
Paraplegic – leg strength	217 (22)	202 (33)	179 (19)	163 (25)	190
Control – leg endurance	112 (14)	115 (15)	123 (12)	132 (13)	120
Paraplegic – leg endurance	99 (15)	106 (13)	115 (13)	121 (12)	110

($P < 0.05$). The paraplegic patient groups were significantly stronger than the controls in any age group examined ($P < 0.01$). Further, when comparing the strength in the younger (20–30 years) with the older (more than 51 years) subjects suffering paraplegia, there was no significant loss of handgrip strength with age ($P > 0.05$). In contrast, while the strength of the knee extensors was significantly higher at any age for the controls (697 N) than paraplegics (average was 190 N) ($P < 0.01$), both the control and paraplegic groups showed a reduction of strength in their quadriceps muscles associated with ageing.

The endurance of the handgrip contractions was always longer than that of the quadriceps contractions at 40% MVC. For example, Table 2 shows handgrip endurance for both the controls and paraplegics was greater than 135 s irrespective of the age of the subjects while for the leg muscles the endurance was always less than 135 s for both the control and paraplegic groups at any age. Typically, for example, the mean (SD) endurance of an isometric handgrip contraction for the controls aged 20–30 years was 135 (13) s while that of their quadriceps muscles averaged 112 (14) s in the same age group. The control subjects, for each age group, had significantly higher endurance in the arm compared to the leg muscles. This was true for all four age groups ($P < 0.05$ for each group). For the leg muscles, the endurance of each of the four age groups in the control subjects was significantly higher than in the same age groups in the paraplegic groups when comparing data in the 20–30, 31–40, 41–50 and more than 50 year-old-groups ($P < 0.01$ for all four comparisons).

Cardiovascular changes

Isometric handgrip

The results of the determination of the average systolic, diastolic and mean blood pressures are shown in Fig. 1 and Tables 3 and 4. For all groups of subjects and for both the paraplegic and control groups, the blood pressure response showed a similar course throughout the duration of the contractions. In Fig. 1, for example, the average systolic, diastolic and mean blood pressures determined at rest (0), and at 20%, 40%, 60%, 80% and 100% of the duration of a fatiguing isometric contraction of the handgrip muscles in the control groups between the ages of 20 and 30 years are shown. As shown in Fig. 1, the blood pressures of these control subjects increased almost linearly throughout the duration of the exercise to a final value about 50% above that at rest.

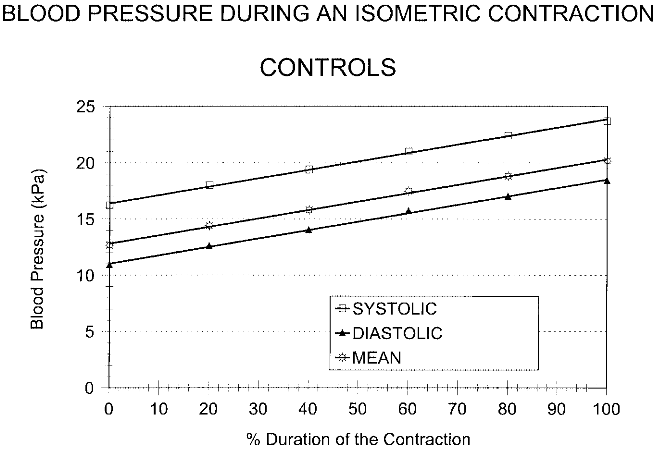

Fig. 1 The average systolic, diastolic and mean blood pressures determined at rest (0), and at 20%, 40%, 60%, 80% and 100% of the duration of a fatiguing isometric contraction of the handgrip muscles at 40% of maximal voluntary contraction in the control group for subjects aged 20–30 years

There was little difference in the response to isometric handgrip contractions maintained to fatigue in the paraplegic and the other control groups irrespective of their ages. For all groups, the systolic and diastolic blood pressures rose linearly from rest to a final value over 50% higher than the pressure at rest during fatiguing contractions of the handgrip muscles. As shown in Table 3, the peak blood pressures recorded at 100% of the duration of the contractions (both systolic and diastolic) rose to similar levels when comparing individual age groups in the controls with those in the paraplegic patients. There was no significant difference in the peak systolic and diastolic blood pressures when comparing paraplegic patients to controls in the 20–30, 31–40, 41–50 and more than 50 year-old-groups to each other ($P > 0.05$). However, for both the paraplegic patient and control groups as shown in Table 3, the blood pressure at rest was higher in older individuals. This increase in systolic and diastolic blood pressures at rest was exacerbated during the handgrip exercise with the peak pressure at the point of fatigue being increased in

Table 3 Mean (SD) systolic and diastolic blood pressures (kilopascals) and heart rate (beats per minute) in control and paraplegic subjects during a fatiguing isometric handgrip contractions at 40% maximal voluntary contraction

Group	Ranges of age (years)			
	20–30	31–40	41–50	51–65
Control – systolic, rest	16.1 (1.2)	16.4 (1.1)	17.2 (1.2)	18 (1.1)
Paraplegic – systolic, rest	15.2 (1.1)	15.6 (0.9)	16.4 (1.5)	16.8 (1.1)
Controls – diastolic, rest	10.4 (1.5)	10.7 (1.2)	11.1 (1.6)	11.3 (1.1)
Paraplegics – diastolic, rest	9.6 (1.5)	10.0 (1.5)	10.4 (1.2)	10.9 (1.6)
Controls – systolic, peak	24.1 (0.3)	24.7 (1.2)	25.2 (1.7)	26.5 (1.9)
Paraplegics – systolic peak	23.9 (2.9)	24.8 (1.6)	25.7 (2.4)	26.8 (2.9)
Controls – diastolic, peak	17.6 (2.0)	18.3 (1.6)	18.8 (1.2)	19.2 (1.9)
Paraplegics – diastolic, peak	12.9 (1.7)	18.4 (1.5)	18.8 (1.5)	19.6 (2.0)
Controls – heart rate, rest	73 (6)	74 (7)	79 (6)	78 (8)
Paraplegics – heart rate, rest	78 (7)	75 (8)	80 (6)	82 (7)
Controls – heart rate, maximal	120 (5)	114 (7)	108 (8)	101 (11)
Paraplegics – heart rate, maximal	85 (8)	85 (9)	88 (6)	88 (7)

older individuals. The paraplegic patients, for example, showed increases systolic/diastolic blood pressures in the 20–30 year-old-group of 8.7/5.9 kPa, respectively, while the oldest group had increases of 10.0/8.3 kPa. There were no differences in the systolic or diastolic blood pressures at rest either before or at the end of exercise between the paraplegic patient and control groups ($P > 0.05$). While the increases in blood pressures (both systolic and diastolic) with ageing were significant ($P < 0.01$) for both paraplegic patient and control groups, there was still no difference between the groups at any age in terms of the blood pressure response to isometric handgrip fatiguing contractions.

The changes in systolic and diastolic blood pressures at any age were no different between the controls and paraplegic patients during the fatiguing isometric contractions of the quadriceps muscles (Table 3 compared to Table 4). There was no statistical difference in the blood pressure for each subject when comparing his blood pressure responses during handgrip contractions and quadriceps contractions ($P < 0.05$). The only common denominator between handgrip and leg extension exercise was that there was an increase in both pressures with ageing.

The heart rate increased linearly throughout the duration of the fatiguing isometric contractions of the handgrip muscles for all subjects. For example, rather than showing individual results, the data from the 20–30, 31–40, and 41–50 and above 51 year-old-groups have been pooled and averaged and shown as single points in Fig. 2. This figure shows the average heart rate determined at rest (0), 20%, 40%, 60%, 80% and 100% of the duration of a fatiguing isometric contraction of the handgrip muscles. The increase in heart rate was almost perfectly linear throughout the duration of the fatiguing isometric handgrip contractions. The correlation coefficient between heart rate and time was 0.96. The slope of the regression line was significantly different from 0 ($P < 0.01$).

The heart rate response to the isometric handgrip contractions as a function of age and paraplegia is shown in Table 3 for heart rate at rest and at the end of the fatiguing contraction for each of the control and paraplegic subject groups subdivided into four groups by age. As shown here, there was a slight increase with age in heart rate at rest in the controls (age range 20–30 years = 73 beats·min^{-1}, age range 51–65 years = 78 beats·min^{-1}) and the paraplegic subjects (age range 20–30 years = 78 beats·min^{-1}, age range 51–65 years = 82 beats·min^{-1}). This increase was significant ($P < 0.05$). The maximal heart rate, in spite of a higher heart rate at rest, decreased with age as shown in Table 3 for controls and paraplegics during isometric handgrip contractions.

Table 4 Mean (SD) systolic and diastolic blood pressures (kilopascals) and heart rate (beats per minute) in control and paraplegic subjects during a fatiguing isometric quadriceps contraction at 40% maximal voluntary contraction

Group	Ranges of age (years)			
	20–30	31–40	41–50	51–65
Controls – systolic, rest	16.1 (1.2)	16.4 (1.1)	17.2 (1.2)	18.0 (1.1)
Paraplegics – systolic, rest	15.2 (1.1)	15.6 (0.9)	16.4 (1.5)	16.8 (1.1)
Controls – diastolic, rest	10.4 (1.5)	10.2 (1.2)	11.1 (1.6)	11.3 (1.1)
Paraplegics – diastolic, rest	9.6 (1.5)	10.0 (1.5)	10.4 (1.2)	10.9 (1.6)
Controls – systolic, peak	24.7 (1.7)	24.9 (1.3)	25.5 (1.5)	26.8 (2.0)
Paraplegics – systolic, peak	23.3 (2.0)	23.5 (1.7)	24.0 (2.1)	25.5 (1.9)
Controls – diastolic, peak	17.9 (1.7)	18.4 (1.5)	18.9 (1.6)	19.6 (2.1)
Paraplegics – diastolic, peak	17.3 (1.5)	17.6 (1.6)	17.9 (1.5)	18.7 (2.0)
Controls – heart rate, rest	73 (6)	74 (7)	79 (6)	78 (8)
Paraplegics – heart rate, rest	78 (7)	75 (8)	80 (6)	82 (7)
Controls – heart rate, maximal	125 (6)	120 (5)	110 (7)	102 (9)
Paraplegics – heart rate, maximal	84 (8)	86 (10)	85 (5)	88 (6)

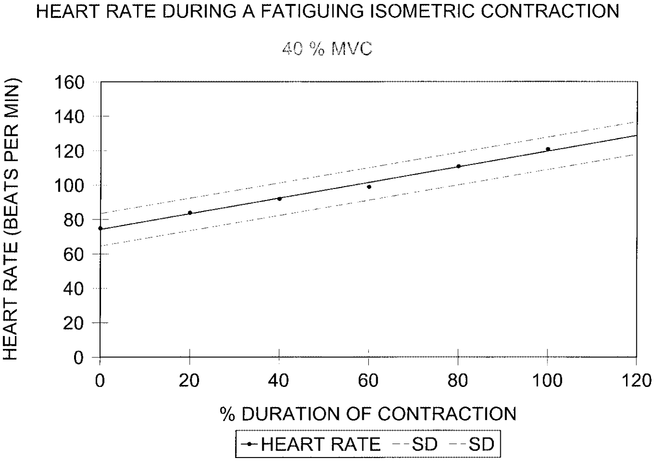

Fig. 2 The average heart rate determined at rest (0), and at 20%, 40%, 60%, 80% and 100% of the duration of a fatiguing isometric contraction of the handgrip muscles at 40% maximal voluntary contraction in the pooled control groups (50 subjects)

Isometric leg extension

While blood pressure at rest was the same with ageing during fatiguing contractions of the quadriceps muscles, the pressure during exercise was different. As shown in Table 4, the systolic and diastolic blood pressures at the end of the fatiguing isometric contraction of the quadriceps muscles was slightly higher in the controls during fatiguing leg extension than isometric handgrip exercise; these differences however were not significant at any age. ($P > 0.05$). The response of the paraplegic patients, however, was slightly less during leg contractions maintained to fatigue due to electrical stimulation than was the case for voluntary isometric contractions of the handgrip muscles. This difference however, while statistically significant using a paired Student's t-test, ($P < 0.05$) for any age, was minimal, amounting to less than 1.3 kPa in most cases. Associated with ageing, as was the case for fatiguing handgrip contractions, the maximal systolic and diastolic blood pressures increased with ageing as shown in Table 4.

Heart rate, on the other hand, increased at rest with age in both groups (controls and paraplegics). Heart rate for the four paraplegic groups did not increase above rest during fatiguing contractions of the quadriceps muscles.

Discussion

Various studies on ageing all point to a gradual loss of strength from age 20–60 years followed by a more rapid loss of strength above age 60 years (e.g. Petrofsky and Lind 1975a, b). In our previous study on ageing and isometric strength, we found that strength declined with age for the handgrip muscles. Endurance, on the other hand, for fatiguing isometric exercise increased with age (Petrofsky and Lind 1975a, b). In the present investigation we also found a reduction in strength in the handgrip muscles in the controls and in paraplegic subjects with age. However, the loss in handgrip strength associated with age was much smaller in the paraplegic subjects than in the controls. The mechanism may be related to central nervous system changes associated with the ageing process.

With ageing, neurons die in the central nervous system (Guttman and Hanzlekova 1972). This death results in the denervation atrophy of motor units and hence a reduction in strength (Guttman and Hanzlekova 1972; Petrofsky and Lind 1975a, b). Even in well-trained athletes, there is still a reduction in strength as they age but the loss in strength is much less than in the population at large (Neder et al. 1999). The paraplegic patients would be analogous to the well-trained athletes to the extent that by continual wheelchair use they stay well trained for hand and arm exercise whereas the controls do not. Therefore, the paraplegic patients, while showing a small reduction in handgrip strength as they age, still had more strength at any age than controls and less of a loss in strength as they aged.

The strength of the quadriceps muscles was also lost with ageing in the controls and paraplegic patients even when electrical stimulation was used to elicit contractions in the paraplegic group for leg extension exercise. If the age related loss had been linked to central command, this would not have been the case. Since the loss in strength occurs even with electrical stimulation, the concept of a loss of motor units is supported by these data.

An increase in endurance associated with ageing for the handgrip and quadriceps muscles was seen in both groups of subjects. The increase in endurance may be attributed to a change in the fiber composition of the muscles. As we age, fiber type in muscle may vary (Guttman and Hanzlekova 1972). Fast twitch units, the units associated with strength but low endurance, are affected more by age than are slow twitch units (Guttman and Hanzlekova 1972). The increase in endurance could be due to the change in the fiber composition of the muscles since increasing endurance-type motor units would favor an increase in the ability to maintain activity longer. This may be compounded in paraplegic subjects since, for their leg muscles, paralysis also causes a shift in fiber composition toward slow twitch, high endurance motor units (Schantz et al. 1997).

Part of the increase in endurance may be also linked to a reduction in intramuscular pressure. The stronger a muscle contraction the higher the intramuscular pressure (Petrofsky and Hendershot 1984). If muscle weakens as we age, then a reduction in pressure would allow more perfusion of blood during exercise. This in turn would allow an increase in endurance (Petrofsky and Hendershot 1984).

Blood pressure at rest increases (both systolic and diastolic) as we age (Petrofsky and Lind 1975a, b). This same principle holds for the magnitude of the blood pressure reflex to a fatiguing isometric contraction

(Petrofsky and Lind 1975a, b). In the present investigation, while paraplegic subjects also showed an increase in blood pressure at rest both before and at the end of exercise associated with ageing, this group had a larger change in blood pressures both at rest and during exercise associated with ageing than did the controls.

This may be attributed to a decrease in compliance in the aortic tree. The increase in blood pressure has been attributed to an increase in cardiac output in the face of a small increase in vascular resistance (Petrofsky 1982). Spinal cord injury causes long-term damage to the cardiovascular system. Premature ageing of the cardiovascular and other body systems occurs in spinal-cord-injured individuals reducing their lifespan and bringing about long-term medical complications (Charlifue et al. 1999). Recent studies show that orthopedic injuries are common in both paraplegics and quadriplegics, (Barber et al. 1996) endocrine changes accelerate with ageing in people suffering paralysis (Bauman et al. 1999), sympathetic nerve impairment, a side effect of paraplegia, increases thermoregulatory stress during exercise (Normell and Wallin 1974), gastrointestinal function is impaired (Stone et al. 1990) and the occurrence of diabetes is much higher in spinal-cord-injured people than in the general population (Karlsson 1999a, b). These changes in the endocrine and sympathetic nervous systems may be indicative of premature ageing of the entire cardiovascular system which, in turn, would result in a faster rise in blood pressure with age in spinal-cord-injured individuals by reducing compliance in the aorta.

The interesting point is that with half of the sympathetic nervous system destroyed by a spinal cord injury, the pressor response is not diminished by the exercise of limbs innervated from above or below the lesion. Muscle is innervated extensively by types 3 and 4 nerve fibers in the interstitial space (Ranson and Davenport 1931; Hnik et al. 1969). These sensory fibers have been linked to a sympathetic reflex increasing blood pressure during exercise. The blood pressure increase is blocked if exercise is conducted on the affected side in a patient having unilateral syringomyelia where sensory afferents have been destroyed even though the muscle strength was unaffected and exercise could be sustained to fatigue (Lind et al. 1968). Here, with the spinal cord injury situated in the middle of the thoracic cord, exercise of limbs innervated from above or below the injury could only activate a portion of the sympathetic afferents since the sympathetic nervous system has been severed. Exercise in the leg would only activate sympathetic fibers below T4. The converse is true for arm exercise. And yet, with a portion of the sympathetic system destroyed, the pressor response is so potent as to be the same as in controls who have their sympathetic systems intact.

Heart rate increased modestly during a fatiguing isometric contraction. The mechanism is believed to be due to central command and not part of a peripheral reflex (Freyschuss 1970) The response is believed to be initiated by a withdrawal of vagal tone followed by an increase in sympathetic nerve activity to the heart (Freyscuss 1970,1980) The notion of a withdrawal of vagal tone at the onset of isometric contractions is supported in studies on obese men with parasympathetic impairment, where the initial increase in heart rate during an isometric handgrip contraction was shown to be impeded compared to controls (Valensi et al. 1999) The maximal heart rate at the end of a fatiguing isometric contraction appears to be related to the tension exerted during the contraction but independent of the muscle mass involved (Funderburk et al. 1974; Silva et al. 1999) Here, as in previous studies, while the heart rate response to isometric exercise was normal for both the control and paraplegic subjects when accomplishing fatiguing contractions of their handgrip muscles, the response, present during leg exercise in the controls, was absent in the paraplegic patients during electrical stimulation and was unaffected by ageing. As in previous studies, the heart rate response appears to be centrally mediated and would be blocked by a complete spinal cord injury since there is no central command to initiate movement and no feedback from sensory afferents to the brain when the contraction is maintained.

Clinically, isometric exercise is a common part of physical therapy. It has been used as a diagnostic tool for coronary artery disease (Petrofsky 1982; Afridi et al. 1998), to strengthen muscle, or as a component of other exercise such as weightlifting where there is a large isometric component (Petrofsky et al. 1975). It is used to stabilize the body in braces or in a standing frame. Whereas the stress of standing may only be 5%–10% of muscle strength in able-bodied people, in the disabled having partially paralyzed muscles, it may require isometric contractions at more than half of their strength. The present investigation points to the need to be careful in the rehabilitation of older patients since the cardiovascular stresses may be high.

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