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THE IMPORTANCE OF OXYGEN TRANSPORT, STRENGTH AND FLEXIBILITY IN MAINTAINING INDEPENDENCE OF THE ELDERLY

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Abstract

This brief review looks at the importance of maximal oxygen transport, muscle strength and flexibility as factors in maintaining the independence of elderly people. The progressive deterioration in these functions observed in middle-aged adults continues at least equally rapidly during the retirement years. Institutionalization seems necessary if maximal oxygen intake drops below a critical threshold, about 18 ml/[kg.min] in men, and 15 ml/[kg.min] in women. A loss of muscle strength and power also increases the risk of institutionalization, particularly in women, although it is less clear whether this risk is independent of effects due to the loss of aerobic power. Regular physical activity can slow or reverse deterioration in oxygen transport, strength, flexibility and balance, thus reducing biological age by 10 or more years. It seems likely that the need for institutional support will be postponed in parallel fashion. It is still necessary to clarify the importance of a deterioration in oxygen transport, strength and flexibility relative to other possible reasons for institutionalization, such as a catastrophic illness. Nevertheless, regular physical activity should be recommended to all seniors, since it can enhance fitness and counter other problems that might lead to institutionalization.

Key words: *activities of daily living, aging, functional capacity, independence, physical limitaions*

Introduction

The ability to live independently is an important factor in maintaining a good quality of life for the very old. A progressive, age-related deterioration in oxygen transport, muscle strength and joint flexibility eventually brings many seniors to the point where their functional capacity is inadequate to sustain independence. Sedentary seniors often reach this threshold at an age between 80 and 90 years (1). In addition to physiological status, critical determinants of independence are the physical demands imposed by the home environment and the degree of social support that is available. We have previously argued that independent living would be very difficult if the maximal aerobic power dropped below 12-15 ml·kg^{-1}·min^{-1} (1,2); we here extend this concept, exploring how far continued independence may be threatened by an age-related deterioration in a range of biological functions, including not only oxygen transport, but also muscle strength, flexibility and balance.

A well-designed regimen of progressive endurance training can reverse much of this functional loss. For example, an effective programme can increase the maximal aerobic power of an older person by 5-10 ml·kg^{-1}·min^{-1} (3) Assuming an age-related loss of about 5 ml·kg^{-1}·min^{-1} per decade of life) (1), this effectively reduces the biological age of an active person by 10-20 years. Parallel calculations can be made for loss of strength and flexibility. The reduction in biological age in turn should prolong independence, greatly enhancing the individual's quality-adjusted lifespan (4).

The present review examines evidence on several issues related to habitual physical activity and independence, seeking answers to five specific questions:

1. Does the rate of loss of oxygen transport, muscle strength and flexibility seen between the ages of 20 and 60 years continue or even accelerate during the retirement years?
2. Is deterioration in some aspect of physical fitness a common reason for loss of independence?
3. How far can regular physical activity prevent and/or reverse the age-related loss of function in the average senior?
4. Is there empirical evidence that regular physical activity reduces an individual's risk of becoming dependent?
5. How far can regular physical activity counter the loss of independence from causes other than decreases in oxygen transport, strength and flexibility?

1. Rates of functional loss in seniors

Maximal oxygen intake. There has been some debate as to the best method of expressing the age-related loss in maximal oxygen intake. Some investigators express data in absolute units ($l \cdot min^{-1}$) rather than relative to body mass ($ml \cdot kg^{-1} \cdot min^{-1}$). This has the apparent advantage of reducing the influence of an accumulation of body fat upon the reported score. However, most of the common daily activities of an old person, such as walking, involve the displacement of body mass against gravity, and the energy cost is then closely related to the individual's body mass (5). Thus, the traditional relative units ($ml \cdot kg^{-1} \cdot min^{-1}$) seem the most appropriate method of expressing functional change in an elderly population.

Should reliance be placed on longitudinal or cross-sectional data? Much of the available longitudinal data has been collected over too short a period to calculate reliable slopes for the aging process. Data then become very vulnerable to short-term increases or decreases in training intensity and frequency. Probably for this reason, some reports have suggested function remains unchanged for many years, and other studies describe an improbably large deterioration of function over just a few years (1). Inter-generational differences in body dimensions and the overall secular trend to a decrease in habitual physical activity have some distorting effect on cross-sectional estimates of functional loss, but nevertheless, the values reported are more consistent than for longitudinal data. In men, maximal oxygen intake decreases at a fairly steady rate from around 45 $ml \cdot kg^{-1} \cdot min^{-1}$ at the age of 20 to 25 $ml \cdot kg^{-1} \cdot min^{-1}$ at the age of 60 years, a slope of 5 $ml \cdot kg^{-1} \cdot min^{-1}$ per decade (6). In women, losses begins around an age of 35, with maximal oxygen transport decreasing from around 38 $ml \cdot kg^{-1} \cdot min^{-1}$ to 25 $ml \cdot kg^{-1} \cdot min^{-1}$ at 60 years of age; again, the rate of loss is about 5 $ml \cdot kg^{-1} \cdot min^{-1}$ per decade (3,7) In some studies, a decrease in physical activity and accumulation of body fat account for about a half of this change (8). This may explain why the rate of loss is somewhat slower in continuing athletes (a slope of around 3-4 $ml \cdot kg^{-1} \cdot min^{-1}$ per decade) (6).

Habitual physical activity may increase when a person first retires, because more leisure time is available (9), but as aging continues, social constraints such as lack of a partner or problems of transportation tend to limit opportunities for physical activity. It is difficult to determine the average rate of functional loss for an elderly population, since most studies of seniors have been based on a minority of healthy survivors who still have sufficient fitness to live independently and participate in experimental studies. One cross-sectional study examined some 400 adults aged 55 to 85 years who were living in London, Ontario. It found that peak oxygen intake decreased in an exponential manner; there was a loss of some 16% per decade, and the lowest values seen in those who were still living independently were 18 $ml \cdot kg^{-1} \cdot min^{-1}$ in men and 15 $ml \cdot kg^{-1} \cdot min^{-1}$ in women (10,11). Longitudinal data for the same population showed a steady decrease in maximal oxygen intake of 4.3 $ml \cdot kg^{-1} \cdot min^{-1}$ per decade in men; in women, the loss averaged 1.9 $ml \cdot kg^{-1} \cdot min^{-1}$ per decade, but perhaps because of a healthy survivor effect, the oldest women showed little loss over ten years of observation (12). Somewhat larger losses, 6.9 $ml \cdot kg^{-1} \cdot min^{-1}$ per decade in men, and 3.9 $ml \cdot kg^{-1} \cdot min^{-1}$ per decade in women were observed in another 6-year longitudinal study of 253 men and 339 women initially aged 70 years (13). The Baltimore Longitudinal Study of Aging (based on 375 men and 425 women) collected longitudinal data over an average interval of 7.9 years; it found a greater loss of function in older participants (5% per decade in young adults, but 20% per decade, or around 4 $ml \cdot kg^{-1} \cdot min^{-1}$ in the middle-old and old-old age categories) (14). Despite some disagreement between these various studies, it seems reasonable to conclude that maximal oxygen intake decreases by at least 4-5 $ml \cdot kg^{-1} \cdot min^{-1}$ per decade during old age.

Muscle strength, flexibility and balance. Muscle strength and flexibility also deteriorate progressively as a person becomes older. There are again issues of measurement technique. Should one examine muscle mass, strength, or peak power? Which muscles are critical to performing the activities of daily living? And are there individual muscle groups that can serve as overall indices of the deterioration in functional status?

One index of overall muscle function is an individual's lean body mass. However, interpretation of such data is complicated by age-related factors that decrease a person's strength per unit cross-section or kg of muscle (15,16). Problems include a progressive infiltration of the muscle by fat, a change in the relative proportions of fast and slow twitch muscle fibres (17), sub-optimal recruitment and synchronization of motor unit activity (18) and a possible differential loss of tissue between the muscles of the upper and lower extremities (19). Master's athletes may show little loss of lean tissue until the sixth or even the seventh decade of life (6,20). Sedentary individuals typically conserve their muscle to around 40 years of age, but thereafter they show an accelerating loss of contractile tissue, such that by the age of 80 years lean tissue mass has decreased 40% in men and 20% in women (21).

Measurements of peak muscle force show a similar general picture. Given the selective loss of fast twitch muscle fibres (17), function deteriorates fastest in rapidly contracting muscles, although losses are smaller for eccentric than for concentric movements (22,23). In older adults, measurements of maximal handgrip force are said to offer a fairly representative index of function in other muscle groups (24). Rather similar losses of strength have been reported in cross-sectional and longitudinal studies (25). Force peaks around 30 years of age, but then shows little change until 50 years; thereafter, the average person shows an accelerating loss of strength (25,23). At age 65 years, the cumulative deterioration of function is about 20%, but by the age of 85 it approaches 40 per cent (26). A 4-year longitudinal study of retirees found that at this stage in life, losses were as large as 2 per cent per year (27).

Recent authors have suggested that an age-related loss of muscle power (force · velocity of contraction) has greater functional significance than the loss of muscle force *per se* (28,29). Unfortunately, information on the deterioration of muscle power is quite limited, although the rate of loss seems greater in women than in men (30). Changes are likely to exceed those imputed from changes in lean tissue mass or peak isometric force, particularly when rapid contractions are attempted, as in righting movements. Another potentially critical issue for an older person is the ability to sustain and to recover from a prolonged bout of muscular activity (31). Available evidence points to the conclusion that at some point in late old age, various aspects of muscle function deteriorate to a point that challenges performance of the simplest tasks of daily living such as climbing a standard step (32,33) walking up a slight slope, or even lifting the body out of bed.

Progressive structural changes in collagen reduce the flexibility of most joints as a person ages. Losses in this aspect of function have been documented most fully in terms of the simple "sit-and-reach" test. Between the ages of 25 and 65 years, the distance of a forward reach observed in cross-sectional data decreases from 0.30 to 0.22 m in men, and from 0.33 to 0.28 m in women (34). Unfortunately, changes in score on this test do not correspond very closely with age-related losses of function at other joints (35). A cross-sectional study of subjects aged 45-74 years found that sit-and-reach scores decreased by about 10% per decade; the loss of shoulder extension as determined by goniometer was of a similar order, but external rotation of the shoulder decreased by only 2% per decade, and there was no significant change of internal shoulder rotation. Likewise, hip flexion showed no change over this age span, and the decrease in head rotation was only 3% per decade. Any restrictions of joint movement are commonly compounded by arthritis, but it is not clear how far the cumulative loss of function limits eventual independence. One report noted that at the age of 79 years, hip motion was significantly limited in only 11% of men and 5% of women (36).

Falls become progressively more frequent in older individuals. Contributing causes include a deterioration of balance, loss of vision, and a slowing of righting reflexes (37). Resulting fractures are a common cause of temporary or permanent loss of independence.

2. Contribution of functional deterioration to loss of independence

Cross-sectional correlations suggest that a wide variety of physical, psychological and social factors may precipitate functional loss and/or disability. Among these items, a low level of habitual physical activity, tiredness, a slow walking speed and poor aerobic function are frequently noted (38-40).

We had originally postulated that independence would be challenged when an individual's maximal oxygen intake had dropped to 12-15 $ml \cdot kg^{-1} \cdot min^{-1}$(1). This view was based on a study by Bonjer (41), who found an exponential relationship between the acceptable duration of aerobic effort and its relative intensity. In his experiments, fatigue was seen if the effort exerted over an 8-hour day exceeded 40-50% of a person's maximal oxygen intake. We reasoned that if the maximal oxygen intake of an elderly person had dropped to 4 METs (14 $ml \cdot kg^{-1} \cdot min^{-1}$), he or she would be able to undertake only a very limited range of activities requiring an energy expenditure of less than 2 METs, and this would make it difficult or impossible to live without assistance. Fleg and associates (14) also argued that the age-related decrease in oxygen transport would progressively bring seniors to the point where loss of independence became almost inevitable. Weiss and associates noted that the simple act of standing caused their oldest subjects to use a half of their maximal oxygen intake of 13 $ml \cdot kg^{-1} \cdot min^{-1}$ (42).

Paterson and colleagues reported that the lowest values of maximal oxygen intake seen in seniors who were still living independently were 18 $ml \cdot kg^{-1} \cdot min^{-1}$ in men, and 15 $ml \cdot kg^{-1} \cdot min^{-1}$ in women (11). A longitudinal study of 297 healthy subjects, initially aged 70 years, found that 43 became dependent over 8 years; a logistic regression noted that age, maximal oxygen intake and the development of disease were all significant predictors of subsequent institutionalization (43). The risk of dependency increased by 14 per cent with each 1 $ml \cdot kg^{-1} \cdot min^{-1}$ drop in maximal oxygen intake (43). Others have also noted relationships of disability and institutionalization to a slow walking speed, a short stride length and poor cardiorespiratory fitness or muscle function in the lower extremities (44-48).

Deteriorations in strength and joint function are less frequently cited as causes of dependency, perhaps because such changes can often be countered by environmental adaptations or occasional assistance from neighbours. Nevertheless, weak muscles fatigue more quickly, and critical minima of strength are needed for such daily activities as getting out of a chair, walking and climbing stairs (49). Because strength as a young adult is less in women than in men, problems are more likely in female subjects (30,33) and one report suggests that lower limb power is the strongest predictor of functional status in elderly women (49). A five-year prospective study of 567 initially healthy seniors found that those initially in the lowest strength tertile had a 2-4 times greater risk of becoming dependent relative to the strongest tertile (50). Likewise, problems of balance contributed to the deterioration of ambulation in a sample of 480 subjects older than 65 years (51). However, neither strength nor balance were seen as significant predictors of loss of independence in the study of Paterson et al. (43).

Perhaps because fitness deteriorates during institutionalization, prior admission to a long-term care facility is also a significant risk factor for readmission (52,53).

Nevertheless, it remains difficult to assess the risk of dependency attributable to sub-optimal maximal oxygen intake, strength or balance, because even if studies have begun with a random or representative sample of the target population, only a small fraction of subjects (typically, the healthiest and those with an interest in exercise) usually complete a longitudinal investigation.

3. How far can regular physical activity avert functiuonal losses?

One early study suggested that the response of seniors to a programme of aerobic training was as large as in younger adults, at least if expressed in percentage terms (54). Nevertheless, it is difficult to assess trainability in the elderly. Caution of the subject or the observer may cause an initial test response to be submaximal; if caution is reduced and the post-training test is closer to a true maximum effort, this may give the impression that conditioning has resulted in a very large gain in maximal aerobic power. Alternatively, the conditioning programme may lack challenge, so that the gain in physical condition is less than would have been realized with more rigorous exercise. If maximal oxygen intake is expressed as $ml \cdot kg^{-1} \cdot min^{-1}$, changes are further confused by any loss of body fat or gain of muscle over the training programme.

Recently published information on the aerobic training response of seniors is summarized in Table 1. There is a weak trend for a greater training response with longer periods of conditioning, from a weighted average gain of 12.9% with an 8-10 week programme to 14.1% with 12-18 weeks of training, and 16.9% with 24-52 weeks of conditioning. In three reports with a poor response averaging 7.8 per cent (55-57) a low intensity of training was adopted. In contrast, seven studies with a high intensity and longer period of training reported a superior response, averaging 24.8 per cent (58-64), equivalent to a 6 $ml \cdot kg^{-1} \cdot min^{-1}$ increase in maximal aerobic power, or a decrease in biological age of about 12 years.

Brisk walking is the preferred exercise of many seniors. This is unlikely to yield major gains of strength. However, a 13% gain of quadriceps torque was observed after one year's participation in one progressive walking programme (65). A substantial number of longitudinal studies have evaluated the potential for resistance training in seniors (66-74). In general, the conditioning response has seemed at least as great as at a younger age. Muscle power is increased by light, medium or heavy resistance exercise, but muscle strength and endurance show a dose-response relationship to the intensity of training (28). Fiatarone and her associates provided resistance training for seniors initially aged 72 to 98 years. Their programme induced a 113% increment of local muscle strength, with associated increments of walking speed and ability to climb stairs (18); however, gains in muscle cross-section were relatively small (2.7%), suggesting that much of the response reflected better neuromuscular coordination. Likewise, Frontera et al. were able to induce a 110% increase in the one-repetition maximum force of 60- to 72-year-old subjects over 12 weeks of resistance training (75). Others have reported 100% gains in strength, and 20% gains in power. Plainly, in subjects where muscle force has become a limiting factor, the functional change can be reversed by an appropriate resistance training regimen, although it is less clearly established that this will alleviate functional disabilities or postpone dependency (70).

Increases of flexibility with training are less dramatic than the increases of maximal oxygen intake and strength, but gains of 9-15% have been noted with low impact aerobic dance (76) and with specific flexibility exercises (77,78).

4. Does training reduce an individual's risk of becoming dependent?

The information presented above suggests that the age-related decrease in aerobic power, muscle strength or balance should be prevented or reversed if seniors engage in an appropriately graded conditioning programme. However, it is also pertinent to ask how far seniors retain functional benefits from physical activity that they may have taken earlier in adult life, and whether conditioning either as a young adult or during the retirement years can make a clinically relevant contribution to maintenance of independence.

Physical activity earlier in adult life. Our cross-sectional study showed that independence in old age was associated with physical activity in middle age (79). Christensen and associates also noted that subjects who were active at the age of 70 had an advantage of functional ability five years later, but they did not find any additional benefits if regular physical activity had been undertaken earlier in life (80).

Current physical activity and maintenance of independence. It is difficult to examine relationships between current physical activity and the maintenance

Table 1. *Aerobic training response of elderly subjects (reproduced from R.J, Shephard, Maximal oxygen intake and independence in old age. Br J Sports Med: Apr 2008; doi:10.1136/bjsm.2007.044800)*

Authors	Age (yr)	n & sex	Duration (weeks)	Gain of $\dot{V}O_2$ peak (%)
Short-term training (8-10 weeks)				
Belman & Gaesser (55)	70	6M/F	8	7
Broman et al. (98)	69	12F	8	11
Morris et al. (99)	64	20M	10	13
Perini et al. (99)	74	8M, 10F	8	17
Poulin et al. (100)	67	10M	9	11
Weighted average				12.9
Medium-term training (12-18 weeks)				
Beere et al. (101)	66	10M	13	18
Blumenthal et al. (102)	71	30 M/F	17	10-15
Charifi et al. (103)	73	11M	14	14
Charles et al. (104)	74	12M	14	12
Ferketich et al. (60)	67	21F	12	25-30
Gass et al. (56)	68	36M	12	6-8
Haykowsky et al. (105)	69	15F	12	12-15
Hepple et al. (106)	68	20M	18	17
Levy et al. (62)	68	14M	17	21
Makrides et al. (63)	65	12M	12	38
Pogliaghi et al. (64)	68	12M	12	20
Posner et al. (40)	73	166 M/F	16	11
Takeshima et al. (107)	68	8M, 10F	12	15
Verney et al. (108)	73	10M	14	11
Weighted average				14.1
Long-term training (24-52 weeks)				
Babcock et al. (58)	71	12M	24	20
Binder et al. (109)	83	57M/F	39	13-14
Carroll et al. (110)	71	16M, 22F	26	15
Cononie et al. (59)	72	17 M/F	26	20
Cress et al. (111)	75	27F	50	16
Evans et al. (112)	80	8M, 2F	43-52	15
Govindasay et al. (113)	67	8M	39	12
Kohrt et al. (61)	65	36M, 36F	39-52	23-26
Malbut et al. (57)	85	9M, 12F	24	0 M, 15F
Sheldahl et al. (114)	64	14M	26	11
Woo et al. (48)	73	18M, 16F	26	12
Weighted average				16.9

of independence because of spontaneous variations in activity patterns. A Scandinavian study of 542 healthy people initially > 70 years of age found that there was no change of function in 50 per cent of their sample over an 8-year follow-up; indeed, function had improved in 9 per cent of the sample over this period (81). Some studies have also failed to find a relationship between current leisure activity and subsequent independence (43,82,83). Presumably, most of the seniors concerned were taking insufficient physical activity for benefit; nevertheless, the risk of functional loss is smaller in those who report taking deliberate exercise, or walking at least 1.6 km once per week (84,85). A study of 549 subjects initially aged 74 years noted that those who maintained or increased their physical activity had a reduced risk of developing disability as assessed by the Health Assessment Questionnnaire Disability Index (86). Other studies, also, have shown an inverse association between participation in exercise programmes and various indices of disability. Thus,

Table 2. *Reported causes of loss of function, restriction of the activities of daily living and/or institutionalization*

Limiting factor	Author
Difficulty in bathing	Gill et al. (115)
Nutritional status	Gill et al. (116)
Appropriate body mass	Minicuci et al. (117)
Smoking	Stovring et al. (118)
Social isolation	Avlund et al. (119,120)
Socio-economic status	Matthews et al. (121,122)
Physical performance	Gill et al. (123)
Walking speed	Onder et al. (124) Shinkai et al. (125) von Bonsdorff et al. (126)
Low level of physical activity	Berk et al. (86)Christensen et al. (80) Gill et al. (127)Shephard & Montelpare (79)
Tiredness	Avlund et al. (128-130)
Maximal oxygen intake	Paterson et al. (43)
Peak muscle force	Onder et al. (124) Rantanen et al. (50)
Inability to rise from a chair	Gill et al. (127)
Cognitive function	Gill et al. (116,131) Jagger et al. (132) Spiers et al. (133) von Bonsdorff et al. (126)
Vision and hearing	Jagger et al. (132,134)
Low self efficacy	Gill et al. (127)
Depression	Minicuci et al. (117)
Prior disability	Hardy et al. (53)
Arthritis	Jagger et al. (132) Spiers et al. (133)
Long-term back pain	Reid et al. (134)
Illness &/or Injury	Gill et al. (132,135,136)

the LIFE study (87) found that a 12 month programme of moderate intensity physical activity countered the risk of being unable to walk a distance of 400 m, and home-based exercise programme for those aged >75 years improved gait speed and a timed chair stand (88) In newly disabled individuals aged >70 years, a combination of regular physical activity and a greater sense of self-efficacy were thought important factors contributing to a recovery of independence (89).

Power training twice a week for 8-12 weeks improved balance in a group of 112 seniors of average age 69 years (90). However, the overall functional benefits of muscle training remain controversial. A systematic review of 66 trials (a total of 3783 individuals older than 60 years) found that progressive resistance training had a large positive effect on strength, and gait speed was also improved, but there was no evidence of functional improvement or an increase in the health-related quality of life (70).

5. Countering other causes of institutionalization

Conservation of fitness, particularly maximal oxygen intake, increases the likelihood of retaining functional independence, but it is less clear how far regular physical activity will counter other reasons for a loss of independence (Table 2), such as loneliness, a worsening of chronic disease, a severe heart attack, or a stroke.

Group exercise may counter social isolation. There is also good evidence that regular physical activity reduces the risks of obesity, maturity-onset diabetes mellitus, hypertension, myocardial infarction, some forms of stroke, several forms of cancer, and osteoporosis, both in younger individuals (3,91,92) and in old age (1,93,94). Exercise also plays a major role in rehabilitation following myocardial infarction, congestive heart failure or a stroke. There may be some decrease in the likelihood of becoming blind because of a reduced risk of maturity-onset diabetes mellitus, and retention of muscle power reduces the chance of a catastrophic fall. It is less clear whether regular physical activity can slow loss of cognition and reduce the risk of Alzheimer's disease (95-97), although some benefit seems likely from increased cerebral blood flow, increased social interactions (particularly during group exercise), and a decreased risk of cerebral atherosclerosis.

Conclusions

Despite many scientific advances over the past ten years, it remains unclear how often loss of independence is attributable to a deterioration of some component of personal fitness. And among seniors who have been admitted to chronic care, it is even more uncertain whether institutionalization can be reversed by an increase of physical activity. There are large differences in rates of institutionalization if seniors between countries, and it is important to investigate factors underlying these differences. What changes to the immediate home environment and what social services would be most effective in postponing institutionalization? And what would be the cost-effectiveness of preventive measures based on social and environmental change, relative to programmes aimed at promoting the physical fitness of seniors? There is good evidence that the age-related deterioration of physical function continues unabated during retirement, and initially healthy adults, are likely to lose their independence if function drops below a critical threshold; in the case of maximal oxygen intake, the critical value is about 18 $ml \cdot kg^{-1} \cdot min^{-1}$ in men, and 15 $ml \cdot kg^{-1} \cdot min^{-1}$ in women. A loss of muscle power can likewise become a problem, particularly in women. Regular physical activity can slow or reverse deterioration in maximal oxygen intake, strength, flexibility and balance, thereby reducing biological age and mayntaining the biological characteristics needed for independence. It may also address many of the other causes of institutionalization, such as social isolation, chronic disease and medical catastrophes. Programmes designed to increase the physical activity of seniors should thus be an important element of health policy.

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