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Review article

Gait in the elderly

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Abstract

Walking is one of the most common of all human movements. It exists to transport the body safely and efficiently across ground level, uphill or downhill. Walking is learned during the first year of life and reaches maturity around 7 until 60 years. Elderly walking performance then starts to decline and the elderly slow down gradually. Falls are a major cause of morbidity in the elderly and in almost all incidences of falls, some aspects of locomotion have been implicated. With the increased life expectancy of the elderly and their more active lifestyle there is now an emphasis on determining any changes that occur in their gait patterns in order to reduce the frequency of falls, to identify diagnostic measures that are reliable predictors of fall-prone elderly and finally to develop programs for preventing such falls. This review addresses the gait related changes in the elderly in order to pinpoint the effect of normal aging for comparison with different gait deviations related to some pathologies. Spatio-temporal, kinematics, kinetics and EMG data will be reviewed as well as the physiological changes associated with gait and aging. Finally, the selection criteria will be reviewed and recommendation on the urgent need of a valid healthy elderly database will be addressed. © 1997 Elsevier Science B.V.

Keywords: Elderly; Walking; Falls

1. Introduction

In Canada, like in other industrial countries, the elderly group (as defined as ≥ 65 years) represents a growing segment of our population. At the beginning of the 21st century, this group will represent about 21% of the total Canadian population, an increase of more than 12.3% with respect to 1976 [1]. Furthermore, it has been estimated that in the year 2006, more than 47% of the elderly will be aged over 75 years old and this reflects the aging process that affects the sub-segment of the elderly population [2].

Falls is a major cause of morbidity in the elderly and in almost all incidences of falls, some aspects of locomotion have been implicated [3–8]. According to Blake and collaborators [9], tripping has been responsible for about 53% of falls. In their review on accidents involving older people, Lilley and collaborators [10] showed that falls are the leading cause of accidental death for people aged over 75. Retrospective studies showed that about one third of the elderly above 65 years are fall-prone elderly and will experience at least one fall per year [5,11,12] while for the elderly over 80 years, the proportion increases to one half [13]. Fallers tend to have a slower gait velocity [8,14] or impaired gait and are more likely to use a cane than non-fallers [15]. The consequence of falls range from a reduced mobility and independence to various injuries and sometimes to death [10,11,16].

During a fall, the body parts that most often contact the ground are the hands and the hips [17,18]. An important decrease in muscle mass and the associated decrease in the cushioning around the hips [19] is related to malnutrition [20,21] and can partially explain, the high incidence of hip fracture in the elderly

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population [22,23]. In the population over 50 years, the number of hip fractures increases by four times every decade [24]. These hip fractures are responsible for an important loss of independence and 50% of the patients will be admitted to a long term care unit and more drastically, 16% will die within the following 3 months. Not all falls lead to a hip fracture but 90% of hip fractures are caused by a fall [25].

Walking is a learned activity in which the moving body is supported successively by one leg and the other. Dynamic regulation of upright stance is essential to the safe and efficient performance of many activities of daily living. During the single limb support (approximately 40% of gait cycle for each limb) the body is in an inherent state of instability because the vertical projection of the center of mass passes along the medial border of the foot [26] and not within the base of support as suggested by Sudarsky [27]. For the swinging limb, the toe clears the ground by less than a centimeter as it travels at its highest forward velocity [26]. The HAT (head, arm and trunk) segment represents about two thirds of the total body mass and has to be controlled by the hip musculature to avoid tilting. The only period of stability is during double support phase and even during this period the two feet are not completely flat on the ground while the HAT segment travels at it's maximum velocity [28].

Even if walking is performed almost unconsciously and largely automatically [26,27] several sources of information help the subject to control walking. Dynamic walking balance is achieved by integrating sensory inputs from the visual, vestibular and proprioceptive systems [16,29–32] with adequate muscle strength, appropriate neuromuscular timing and free passive joint mobility [33,34]. In normal aging, degeneration of one or more of these sensory systems occurs [35,36] and may compromise balance during walking [37].

In face of the high prevalence of chronic condition and illnesses in the elderly population and their associated social and health costs [38], the scientific and medical communities need to know more about what is the 'normal' gait pattern in the elderly to establish a valid data base for making a comparison with elderly patients that need special care.

In the next sections, the neurological and physiological changes associated with aging will be reviewed and the influence of aging on the gait pattern will be presented using the spatial–temporal, kinematics, kinetics and EMG data. Finally, the authors will comment on selection criteria for healthy elderly and recommendations will be formulated.

2. Neurological changes with aging

An integrated nervous system with sufficient motor drive and adequate sensory feedback is required for efficient locomotion. Delwaide [39] reported loss of motor units and sensitivity as well as peripheral troubles associated with age. Age-related changes in the nervous system include increased reaction times, increased rate of brain loss, reduced level of neurotransmitter production like dopamine and a decreased acuity of the auditory, vestibular, visual and somatosensory systems [40–46]. Particularly for the somatosensory system, the research studies have shown, with advancing age, a decrease in perception of high frequency vibrations, [47] touch, proprioception and pressure stimuli (see review by Alexander [48] and Horak [49]). Even if the majority of investigators agree that the decrease in performance of the nervous system is a natural part of the aging process, there is neither consensus about the rate of age-related change within or across systems, nor about primary factors in accelerating or retarding the aging process.

3. Physiological changes with aging

During walking, more than 1000 muscles are synchronized to move over 200 bones around 100 moveable joints [50]. Gait adaptation as seen in the elderly population may be associated with the general decrease in muscle strength due to loss of motor neurons, muscle fibers and aerobic capacity [34,51,52]. Muscle contraction needs oxygen, so the intensity of muscle work can be assessed by measuring the amount of oxygen used by the muscle during a given task. Even if walking is considered a very complex task, a healthy person walking at self selected velocity, performed this task at a minimal energy cost [28,50]. Waters and collaborators [53] have provided standard tables for energy consumption during walking in a wide range of ages and gait velocities. They concluded that during walking at normal velocity, the elderly (mean age, 68.2 years) consumes significantly more oxygen for a given distance than the young (mean age, 39.2 years) despite the fact that the elderly group walks significantly slower that the young.

Other age-related changes may occur in the joints and can limit movement. The loss of passive range of motion in the elderly is often progressive and subtle. Some factors account to keep a full active range of motion. First, the periarticular connective tissue (PCT) must possess a stiffness level that does not inhibit a joint's total range of motion. PCT includes ligament, associated joint capsule, aponeurosis, tendon, intramuscular connective tissue and skin. All these tissues are physically linked to the joints and therefore their extensibility influences the joint's range of motion. The mechanical properties of PCT do appear to change with advanced age. A mechanism to account for increased stiffness in age-related PCT may be the fact that aged

Table 1
Age and gait velocity parameters in young and elderly subjects

References	Young		Old	
	Age (years)	Velocity (m/s)	Age (years)	Velocity (m/s)
Women				
Öberg et al. [72]	20–29	1.24	60–69	1.15
Hageman [92]	23.9	1.59	66.9	1.32
Finley [91]	29.9	0.84	74.4	0.70
Waters et al. [53]	40.1	1.28	68.9	1.2
Men				
Öberg et al. [72]	20–29	1.23	60–69	1.27
Blanke and Hageman [77]	24.5	1.32	63.6	1.38
Waters et al. [53]	38.5	1.36	67.1	1.28
Mixed				
Elble et al. [66]	30	1.18	74.7	0.94
Cummings [22]	24.6	1.39	61.5	1.33
Winter et al. [76]	24.6	1.43	68.0	1.28
Ostrosky et al. [81]	28.2	1.38	67.4	1.27
Gabell et al. [78]	21–47	1.37	66–84	1.19

collagen shows increased numbers of cross-links between adjacent tropocollagen molecules [54,55]. This process would increase the mechanical stability of collagen and may explain the increased stiffness in the tissue [56].

Excessive joint wear may predispose to osteophyte formation and incongruities at the articular surfaces. These factors could interfere with total joint range of motion. It has been suggested that the slowed volitional joint movement displayed by many elderly subjects can provides additional time for the processing of incoming environment stimuli [57]. Some degree of mechanical degeneration of aged human articular cartilage should be considered a normal process. The wear may be from repeated loading of joint over a good part of the lifetime. The ability of even healthy articular cartilage to dissipate transarticular forces may be decreased in the aged population. Osteoarthritis occurs with greater frequency by the age of 60 and more than 60% of this population may exhibit some degree of cartilage abnormality in some joints [58]. Nevertheless, one can not assume that osteoarthritis is solely a mechanical result of the aging process because not all elderly people develop osteoarthritis.

4. Spatial–temporal variables

Observational gait analysis is actually the initial stage in constructing someones gait pattern (see review by Malouin [59]). Because they needed both very little and non-sophisticated equipment, spatial–temporal variables were the first gait related data to be assessed during locomotion. Minimal equipment has been used for the calculation of walking velocity (a known distance to travel with marks on the floor and a stopwatch). Some equipment has been designed to simplify the measurement of walking speed and this can be performed at the subject's home [60]. Walking speed has been proposed as a valid and practical measure of mobility [61] and reflects activity of daily living function [62]. Ambulation profile index have been proposed for clinical gait analysis [63,64].

In the research on elderly gait, the most consistent finding is that walking velocity decreases with age [26,65–71]. Assuming symmetry, walking velocity is calculated from the step length and step frequency parameters as follow:

$$\text{Walking velocity} = \text{stride length} \times \text{cadence}/120 \qquad (1)$$

Öberg et al. [72,73] have tested a total of 233 healthy subjects with ages ranging from 10 to 79 years. These authors have collected data during slow, normal and fast walking on a 10 m walkway in a laboratory setting. They found a significant sex difference in all basic gait parameters including lower gait velocity and step length with higher cadence in females than in males [72]. Despite the large number of subjects and range of velocities tested, this study lacked details regarding the recruitment and health status of their sample. The specific instructions given to the subjects about the velocity needed to be obtained (slow to fast) are also missing or have not been controlled as in Winter [26] where slow and fast gait are defined as a ± 20% change from their natural cadence. Table 1 shows a review of the data comparing gait velocity in elderly versus young subjects.

Age effect is significant in gait velocity for normal and fast walking speeds [65]. In a study testing 81 women (aged 64–94.5 years) at five different velocities, Leiper and Craik [74] used a multiple-regression analysis and determined that age accounted for 30–45% of the variability in walking velocity. With a study on 1815 elderly subjects over 70 years, Woo and collaborators [8] confirmed these results in women but also included height as well as the level of physical activity as significant factors. However, in their male population, age was the single significant factor affecting gait velocity. The relation between reduction of walking speed and age ranged from 0.1 to 0.7% per year. Stride length is the easiest way to control walking velocity so the slowness of elderly gait can be partially explained by the reduced stride length [66,67,70,71,75,76]. On the contrary, Blanke and Hageman [77] concluded that there was no significant difference between young and elderly men, in step and stride length as well as in gait velocity. Their subject sample was very small ($N = 12$ in each group) and a lack of significance does not mean that there was no difference between their groups. The power of their study was probably too low to detect a difference and the P-value chosen ($P \leq 0.01$) may be too restrictive for such research. A P-value of 0.05 is usually chosen when studying gait [26].

Gabell and Nayak [78] did not observe a significant difference between young and elderly on the variability in gait as measured by the coefficient of variation of step length, stride time, stride width and double-support time. In two studies, the cadence was not different between the young and the elderly [66,76] while in one study there was a significant difference in cadence variability [79].

Major findings on the effect of age on spatio–temporal variables can be summarized as a decrease of the stride length, cadence and velocity. These data did not show which muscles are responsible for these changes. The kinematics will pinpoint the segmental internal aging process on joint angles and range of motion.

5. Kinematic changes and aging

The subjective information given by an observational gait assessment can be confirmed by a quantitative kinematic analysis. A kinematic analysis objectively describes how the body segments of the subject are moving during gait. Electrogoniometer or external marker attached on the segment landmarks allow for angle and range of motion calculation. In gait analysis, generally, the ankle, knee and hip motion are recorded. Winter [26] and Öberg and collaborators [73] reported very minor differences in joint angle profiles between the young and the elderly, but subtle changes occur at the amplitude level. Ankle dynamic range of motion is lower in elderly (24.9°) while in the young it reaches 29.3°. Associated with the decrease in ankle range of motion, is the general ankle plantar and dorsiflexor muscle weakness in the elderly [34,51]. Judge and colleagues [80] reported a reduced peak plantar flexion angle ($13 \pm 5°$) in the elderly compared with the young ($17 \pm 5°$). The elderly also walked with more out toeing foot angle.

The knee extension angle at mid-stance increased by about 0.5° per decade while a decrease by 0.5–0.8° per decade is shown during the swing phase [72,80]. Winter [26] showed that the elderly maintain a slight knee flexion at the end of swing (5.3°) compared to the young who displayed almost a full knee extension (0.5°). This knee flexion in the elderly is performed to decrease the quadriceps demand during loading response and it correlates well with their significant shorter step length [8,67,69,72,76,81,82]. During the gait cycle, the knee range of motion also decreased in the elderly [80] ($55 \pm 5°$) compared to the young ($59 \pm 5°$).

The hip dynamics range of motion is much larger in the elderly [26] (40°) than in the young (32°) but it remains well above the 30° required at heel contact [34]. With gait analysis of 233 persons, Öberg and collaborators [73] did not find any significant differences in the hip angles. The anterior drop of the pelvis in the elderly gait was attributed to the need to put their hip extensors at a more favorable length so they can meet the demand despite the weakness associated with aging [34].

The heel contact skid velocity is also significantly higher (1.15 m/s) in the elderly compared to the young (0.87 m/s) subjects [26] despite the fact that the elderly walk slower than the young. This higher horizontal heel velocity increase the potential for a slip-induced fall in the elderly. Delayed and reduced hamstring muscle activation is associated with this increased horizontal velocity.

Head and hip accelerations have also been investigated. For the antero–posterior direction, Winter [26] reported lower hip accelerations in the elderly (1.54 m/s^2) than in the young (1.91 m/s^2) while for the head, the elderly showed a greater acceleration (0.621 m/s^2) than the young (0.475 m/s^2); thus, the young were able to attenuate the head accelerations by 72% compared with only 58% for the elderly. Attenuation of the head acceleration is warranted for stabilization of the visual platform during locomotion. This attenuation is achieved by the paraspinal muscles and started from cervical level and progressing downward allowing the stabilization of the visual platform [83]. In fact, erector spinea muscles at C7 level is activated about 70 ms before L4 level showing an anticipatory control. Yack and Berger [84] used a triaxial accelerometer attached to the second thoracic vertebrae of 20 elderly (faller and

Table 2
Peak powers at the ankle, knee and hip in the young and elderly subjects

Peak power (W/kg)	Young ($n = 9$) (Eng and Winter [87])	Elderly ($n = 18$) (Prince et al. [88])	Young ($n = 32$) (Judge et al. [80])	Elderly ($n = 26$) (Judge et al. [80])
Age (years)	22	71	26	79
Gait velocity (m/s)	1.6	0.97	1.16	1.03
Cadence (step/min)	108	95	110	116
A1	0.50	0.58	—	—
A2	4.36	1.62	3.50	2.90
K1	0.53	0.29	0.33	0.22
K2	0.38	0.12	0.16	0.17
K3	1.54	0.63	0.77	0.70
K4	1.38	0.47	—	—
H1	1.73	0.81	0.55	0.47
H2	1.04	—	—	—
H3	1.34	0.56	0.87	0.92
H4	0.32	—	—	—

non-faller) and 19 young subjects while walking. With a ratio of the even to odd harmonics they have calculated an index of smoothness of their gait pattern. They found a significant difference between the young and the fall-prone elderly for both antero–posterior and vertical directions. A degeneration of their trunk control may be experienced by the elderly. An alternate explanation is given by Winter [26] and suggested that the vestibular system of elderly might have a reduced gain and thus requires larger acceleration input in order to monitor the head accelerations.

6. Kinetic changes and aging

Very limited information comparing the young and elderly are available on kinetics. Force platform data [26] showed that antero–posterior peak during push-off is less (1.93 N/kg) in the elderly than in the young (2.19 N/kg) showing a less vigorous push-off. Calculation of moment of force requires the knowledge of segment masses and moments of inertia. Anthropometric data list the characteristics of body segments; most of this information is obtained from cadavers studies. For calculating moment of force using an inverse dynamic approach, one should know the inertia of the segment and the position of it's center of mass with respect to bony landmarks. The anthropometric characteristics differ between the young and elderly. Recently, Jensen and Fletcher [85,86] have produced tables for the distribution of mass to the segment and for the body segment moment of inertia. Moment of forces profiles in both young and elderly are reported by few authors. Winter [26], reported that peak ankle plantarflexors are lower in the elderly (1.437 N/m per kg) while it reached 1.628 N/m per kg in the young. The general patterns of power profiles are the about the same in elderly and young subjects but some differences are noticed when the power and work (energy absorbed or generated by the muscle) are compared. While performing a 2-D data analysis, Winter [26] reported that ankle plantarflexor power during push-off is higher in the young (3.266 W/kg at 1.44 m/s) compared to the fit and healthy elderly (2.478 W/kg at 1.29 m/s) showing again a less vigorous push-off for a lower walking velocity in the elderly. When comparing young and elderly subjects (Table 2) using a 3-D protocol, Eng and Winter [87] reported in the young a peak value of ankle plantarflexor of 4.36 W/kg (at 1.6 m/s and 108 step/min) and Prince and collaborators [88] reported a much smaller peak value of 1.62 W/kg for a group of 18 elderly subjects walking at 0.97 m/s and at a cadence of 95 step/min. This elderly sample was screened to represent the general elderly population living in the community. Judge and colleagues [80], reported slightly higher values for both groups and came to the same conclusion, i.e. that the elderly have a less vigorous push-off. Their elderly subjects walked at 1.03 m/s and at a cadence of 116 step/min while their young subjects walked at 1.16 m/s and at 110 step/min. Peak ankle power was also found to be the strongest predictor of step length because it explains more than 52% of the step length variance [80]. As expected, the work done by the plantarflexors is higher in the young than in the elderly (respectively 0.293 vs. 0.190 J/kg).

Knee absorption during the transition between stance and swing is higher [76] in the elderly (0.089 J/kg) than in young adults (0.047 J/kg). Thus the elderly absorbed almost half of the energy generated by the major push-off phase while the young absorbed only 16%. Peak knee absorption power tends to decrease with respect to age during both mid and late swing. This shows less demand on the musculature to reduce leg angular velocity and is directly related to the lower push-off by ankle musculature.

At the hip, Judge and colleagues [80] have shown that hip pull-off power (H3) is a very important contribution (around 16%) to the gait of elderly subjects. The H3 peak power shows an increase with respect to age in Judge and colleagues [80] while it decreased in Prince and collaborators [88].

7. Selection of the population

Ferrandez [82] have screened their elderly population to exclude those with disorders causing pain in walking; vascular and neuromuscular disorders in the lower limbs, motor, sensorial, cerebellar or vestibular deficits from neurological origin, severe cognitive, heart or breathing disorders; major visual defects; depressive or asthesia tendencies. These authors concluded that elderly gait is normal if one takes the gait velocity into account. When comparing gait on a treadmill at the same velocity, Jansen and collaborators [89] have shown a constant gait pattern independent of age and sex. Their subjects were screened for several diseases affecting the spine and the lower limb as well as for cardiopulmonary insufficiency. Bloem and colleagues [90] have shown that we can find a totally normal gait pattern in the subjects over 88 years. Thus, the criteria used for the selection of the old subjects are a very important factor affecting gait performance. Some research have screened very carefully their elderly to the point that only the fit and healthy were recruited [76]. The question arises whether superior fitness represents the norm for the elderly. In order to compare the elderly with gait and balance disorders, we must have a representative healthy elderly population for comparison. It is highly improbable that elderly with gait and balance disorders have above-normal fitness. Thus it is recommended that the comparison group be screened only for gait and balance disorders.

While the advantage of the 3D analysis over the 2-D was clearly demonstrated [87], the literature reporting 3D moments and powers in the gait of elderly is still warranted. Research approaches, including multiple regression can provide insight to the cause of decrease in gait performance with aging. Computer and measurement technology has increased the speed of gait-related variables calculation. Large number of subjects are necessary in order to establish valid data bases which are essential to make a basis of comparison with elderly suffering from different pathologies such as stroke, amputation, peripheral neuropathy and Parkinson' disease.

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