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Effect of Age on Characteristics of Forward and Backward Gait at Preferred and Accelerated Walking Speed

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Background. Backward walking is used increasingly in rehabilitation programs to promote balance, strength, and aerobic conditioning. This study examines the effect of movement direction on the temporal–spatial gait characteristics of old versus young adults when progressing at a comfortable pace and as fast as possible.

Methods. Participants included 40 old (mean age 77.7, standard deviation ± 6.2) and 30 young volunteers (mean age 24.0, standard deviation ± 2.3), who were independent walkers. Using a computer-based walkway system, participants were requested to walk forward and backward at a normal pace and as fast as possible. Analyses of variance and Tukey–Kramer tests were conducted to determine effects of age, movement direction, and acceleration of gait speed on various gait parameters.

Results. Forward and backward walking of elderly persons is generally characterized by a lower velocity, cadence, stride length, and swing phase, accompanied by an increase in the double-support phase. Reversing from forward to backward walking presents a similar pattern in both age groups, with a decrease in gait velocity, stride length, and swing phase, an increase in the double-support phase, and no change in cadence. However, the decrease in stride length is significantly greater among elderly persons. In young persons, higher gait velocities are achieved by concurrent increases in stride length and cadence, regardless of movement direction. Ability of older persons to increase backward ambulation is limited and relies solely on increasing cadence.

Conclusions. Elderly persons demonstrate difficulties in walking backward, with stride length particularly affected. These difficulties must be considered when using backward ambulation for rehabilitation of elderly persons.

AGE-RELATED changes in the gait characteristics of forward locomotion have been studied extensively under a wide range of conditions (1–5). These studies generally demonstrate age to be associated with a decrease in self-selected gait speed, cadence, stride length, and relative duration of the swing phase, accompanied by an increase in single- and double-support time. Nevertheless, studies of persons encouraged to walk at an accelerated speed demonstrate that elderly persons are capable of increasing their gait velocity, stride length, and cadence to levels similar to those of young adults walking at a comfortable walking speed (2,6,7). Thus, to aid in setting rehabilitation goals, norms of the gait characteristics of elderly persons are often presented for both comfortable and accelerated speeds.

In recent years, there has been a growing interest in the use of backward walking (BW) and running for training and rehabilitation purposes. Research findings indicate that these activities are characterized by a lower peak vertical ground reaction force than are forward walking (FW) and running (8). Furthermore, the loading phase of the gait cycle in backward locomotion involves a concentric contraction of the extensor knee mechanism, rather than the more stressful eccentric contraction typical of forward locomotion (9). Thus, BW is associated with less biomechanical strain on the knee joint than is FW. Because research indicates that BW activities are effective means for increasing the strength and power of the quadriceps muscle (10), these activities are now often incorporated in various rehabilitation programs, particularly for disorders in which FW activities aggravate knee pain (10). Moreover, because research suggests that BW can increase energy expenditure to levels high enough to maintain cardiorespiratory fitness (11,12), BW and running are considered attractive exercise alternatives for aerobic training.

There is growing evidence of the positive effects of exercise programs on balance, strength, function, and well-being of older individuals (13–16). Therefore, it is surprising that studies of backward locomotion have focused primarily on young adults (8,9,11,17–20), and that BW activities are not cited as a rehabilitation tool for the elderly population. A preliminary study comparing FW and BW between young and old adults, progressing at a self-selected gait speed, indicates that the changes in the gait characteristics typical of reversing movement direction are accentuated with age (21). Furthermore, studies of age-related differences in the characteristics of maximal rapid stepping indicate a substantial decline in the abilities of older adults to initiate rapid single steps in all directions (22–25). Impairments in these abilities have been shown to be closely related to measures of balance and fall risk (23). To further understand the mechanism of rapid stepping for fall prevention and to properly use BW as a rehabilitation tool for the elderly population, it is important to determine the

Table 1. Age and Height Characteristics of Elderly and Young Participants, Mean ± *SD* (range)

Characteristic	Elderly (20 Male and 20 Female)	Young (15 Male and 15 Female)
Age	77.7 ± 6.2 (65–89)	24.0 ± 2.3 (20–31)
Height	162.6 ± 8.8* (147–179)	168.6 ± 9.0* (151–183)

Notes: *SD* = standard deviation.
*Significant difference, $p = .01$.

backward gait characteristics of elderly persons beyond a single step at both normal and accelerated speeds. Thus, the objective of the present study is to compare temporal and spatial characteristics of young and old adults in FW and BW, progressing both at a comfortable normal pace and as fast as possible.

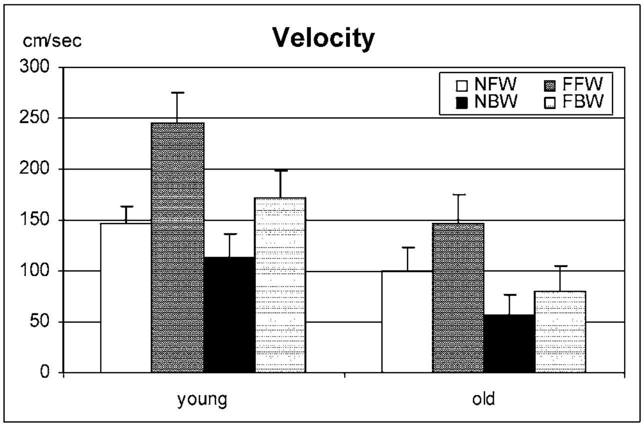

Figure 1. Means and standard deviations of gait velocity in each of the four walking conditions for young and old participants.

Methods

Participants

Our study included 20 male and 20 female elderly volunteers recruited from two community housing facilities for elderly persons, and a group of 15 male and 15 female young volunteers recruited among university students. Participant characteristics are presented in Table 1. Initial screening ensured that all participants were generally active but not trained professionally in sports or dance, and with no known orthopedic or neurological abnormalities that would impair gait. Participants walked independently with no assistive devices and had no history of more than one fall in the last year. The study was approved by the institutional ethics committee, and all participants gave informed consent prior to participation.

Procedure

Data concerning gait characteristics were collected via a computer-based instrumented walkway system (GAIT-Rite; CIR Systems, Havertown, PA). The system consists of an electronic roll-up carpet with an active area of 61 × 366 cm, embedded with pressure sensors placed 1.27 cm apart. Timing of activation and deactivation of each sensor is processed by a personal computer which computes the temporal and spatial characteristics of the gait. Concurrent validity and reliability of the system has been established in previous studies (26–28).

Wearing comfortable clothes and shoes, each participant was asked to walk across the GAITRite mat for the following walk conditions: 1) Normal Forward (NFW); 2) Fast Forward (FFW); 3) Normal Backward (NBW); and 4) Fast Backward (FBW). The instruction for the ''normal'' walks was ''walk at your preferred comfortable normal speed.'' For the ''fast'' walks, the participants were requested to ''walk as fast as possible safely and without running.''

The participants were requested to walk across the walkway for one or two practice trials before each new test condition to familiarize them with the task. Participants were instructed to begin each trial 1 meter before the walkway and to continue at least 1 meter beyond it so as to exclude the starting and breaking steps. The young participants were asked to walk across the walkway back and forth for a total of eight trials for each test condition. However, to limit fatigue effect, the older participants were requested to repeat only six trials for each test condition. Participants were allowed to rest between trials as necessary. For each participant, the order of test conditions was randomized and the data from all trials in each test condition were combined for data analysis.

Analysis

Means and standard deviations were calculated for the following variables: (a) walking velocity (cm/s); (b) stride length (cm), the distance between the heel locations of two consecutive footfalls of the same foot; (c) cadence (steps per minute); (d) percentage of swing phase, the duration of progression of the foot from the previous to the next support position, measured as the percentage of gait cycle; and (e) double-support phase (DSP), consisting of the periods when both feet are in contact with the floor, expressed as the percentage of gait cycle.

The analysis consisted of separate mixed-model three-way analyses of variance (ANOVAs) (2 × 2 × 2) for each variable, with participants as a random factor nested within the participant group and three independent fixed factors as follows: age (young and old), direction (FW and BW), and speed (normal and fast). ANOVAs were followed by preplanned comparisons based on adjusted Tukey–Kramer tests. Student's *t* test for independent samples was used to compare the body height of the two groups. Statistical significance was considered at $p = .05$, and analysis was performed using SAS (version 6.09; SAS Institute, Cary, NC).

Results

Figures 1–5 present the means and standard deviations of gait velocity, stride length, cadence, swing phase, and DSP, respectively, for the young and old participants in each of the four walking conditions. A summary of the main and the

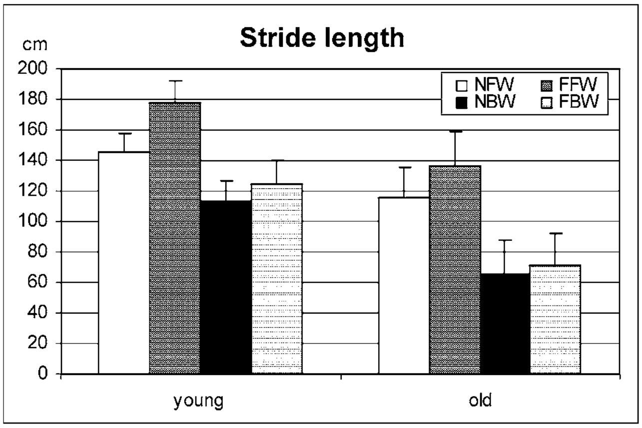

Figure 2. Means and standard deviations of stride length in each of the four walking conditions for young and old participants.

interaction effects of ANOVAs for each of the dependent variables is presented in Table 2.

A main age effect on each of the five variables is supported by the Tukey–Kramer tests, which indicate an age-related decrease in gait velocity, stride length, cadence, and swing phase, accompanied by an increase in the DSP in each of the four gait conditions. Similarly, the reversal of gait direction induces a decrease in gait velocity, stride length, and swing phase, as well as an increase in the DSP, with only cadence unaffected by the reversal of gait direction. Tukey–Kramer tests indicate this to be true in both age groups and at both normal and accelerated speeds, with a few exceptions. First, there is a tendency among the older participants toward a higher cadence in the FBW as compared to the FFW ($p = .066$). Second, both the swing phase and the DSP of the young participants progressing at a normal pace remain unaffected by the reversal of gait direction.

Following an instruction to increase gait speed, both groups are shown to increase their gait velocity significantly by increasing their stride length and cadence, whether

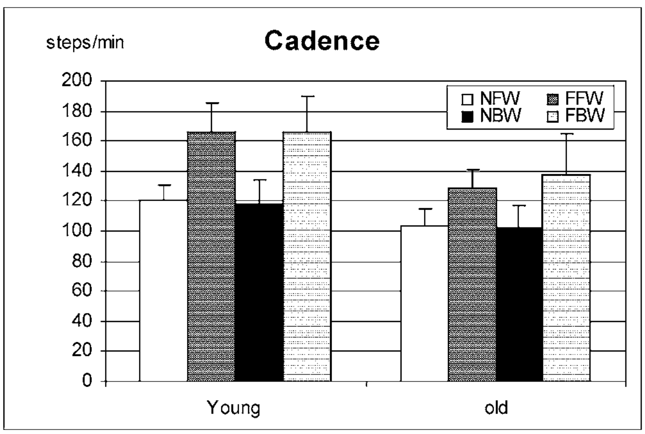

Figure 3. Means and standard deviations of cadence in each of the four walking conditions for young and old participants.

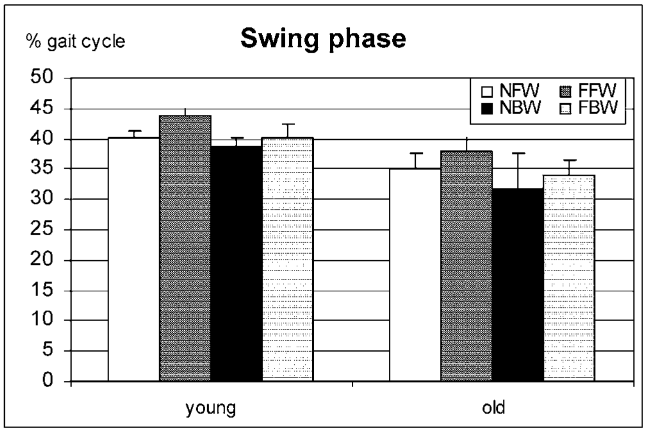

Figure 4. Means and standard deviations of the percentage of gait cycle in the swing phase in each of the four walking conditions for young and old participants.

progressing forward or backward. Tukey–Kramer tests indicate one exception, as older participants are unable to increase their stride length when requested to accelerate their backward gait. Instructions to accelerate speed also induce an overall longer swing phase and a shorter DSP. However, Tukey–Kramer tests indicate that these changes are not present in young participants accelerating their BW.

A significant interaction effect between age and direction is observed only for stride length, indicating a significantly greater decrease in stride length among older participants when gait direction is reversed. The interaction effects between age and speed indicate that when participants are instructed to increase their gait speed, the changes in speed, stride length, and cadence are significantly greater in young adults. However, the relative changes in the swing phase and the DSP follow a similar pattern in both age groups. The interaction effects between direction and speed indicate that the instruction to increase gait velocity is associated with a greater effect on gait velocity, stride length, swing phase,

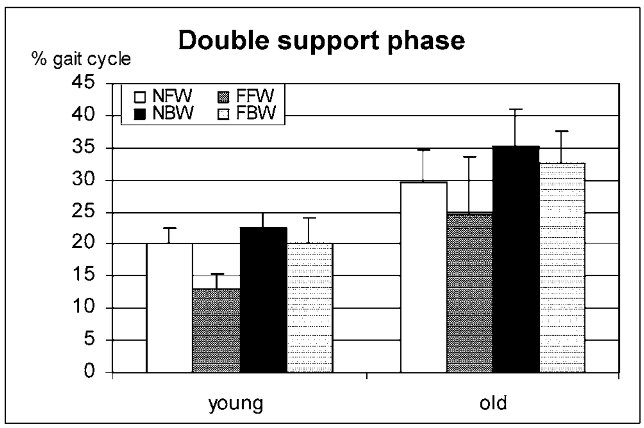

Figure 5. Means and standard deviations of the percentage of gait cycle in the double-support phase in each of the four walking conditions for young and old participants.

Table 2. Summary of ANOVAs for Each of the Dependent Variables (p Values)

Factor	Velocity	Stride Length	Cadence	Swing Phase	Double-Support Phase
Age	<.0001	<.0001	<.0001	<.0001	<.0001
Direction	<.0001	<.0001	NS*	<.0001	<.0001
Speed	<.0001	<.0001	<.0001	<.0001	<.0001
Interactions					
Age × Direction	NS	<.0001	NS	.0594†	NS
Age × Speed	<.0001	.0008	<.0001	NS	NS
Direction × Speed	<.0001	<.0001	.0773†	.0005	.0063
Age × Direction × Speed	.0231	NS	NS	NS	.0684†

Notes: *NS = nonsignificant, $p > .1$.

†Marginal effect.

ANOVA = analysis of variance.

Table 3. Summary of Tukey–Kramer Tests Comparing Old Participants Progressing Forward and Backward at Accelerated Speed With Young Participants Progressing at Normal Gait Speed

Groups Compared	Velocity	Step Length	Cadence	Swing Phase	Double-Support Phase
Young NFW vs Old FFW	NS*	NS	NS	.001 Young > old	NS
Young NBW vs Old FBW	<.0001 Young > old	<.0001 Young > old	.0005 Old > young	<.0001 Young > old	<.0001 Old > young

Notes: *NS = nonsignificant, $p > .1$.

NFW = normal forward walking; FFW = fast forward walking; NBW = normal backward walking; FBW = fast backward walking.

and DSP in the forward direction. The marginal interaction effect between direction and speed for cadence indicates that the same instruction has a tendency to affect cadence more in the backward direction.

Given the difficulty of older participants to accelerate their gait velocity, Tukey–Kramer tests were designed to compare the gait characteristics of older participants progressing at an accelerated speed with those of young adults progressing at their normal comfortable pace. A summary of the Tukey–Kramer tests is presented in Table 3. When older participants are encouraged to walk forward as fast as possible, their gait characteristics resemble those of young adults progressing at their normal pace of comfort, with the exception of the swing phase, which remains shorter in the older participants. In contrast, none of the gait characteristics of the older participants who are progressing backwards as fast as possible reach the level of the young participants who are walking backwards at their normal pace.

Discussion

The examination in the present study of BW among young and old adults at both normal and accelerated speeds presents several interesting results. The age-related differences previously observed in FW (1–3,5) are generally paralleled in BW. Thus, whether progressing at a normal or an accelerated pace, BW of elderly persons in comparison to young adults is characterized by a lower gait velocity, cadence, stride length, and swing phase, accompanied by an increased DSP. Furthermore, the changes in temporal–spatial characteristics occurring when the gait direction is reversed follow a similar pattern in both age groups. Thus, given an identical instruction as to gait velocity, backward locomotion is characterized by lower gait velocity, stride length, and swing phase, accompanied by an increased DSP. The only parameter that remains largely unchanged when persons are requested to reverse gait direction is cadence.

Previous studies of forward gait indicate that, although the preferred normal gait speed of old persons is slower then that of young persons, the actual speed measured in different studies ranges between 83 and 159 cm/s for the young and between 60 and 145 cm/s for the old (4,29). Thus, the present study compared older adults with average speed performance (100 cm/s) with young adults performing at a relatively high level (overall mean = 146 cm/s). An interesting follow-up study would involve a comparison between forward and backward ambulation of young and old adults whose preferred normal forward gait speed is more similar.

Stature has been shown to be moderately correlated with stride length and may affect gait velocity (29). As the elderly participants in this study were significantly shorter than the young participants, the difference in stature between groups may have affected the results. However, although normalizing the results to height may isolate the effect of age from the effect of height, it is often not recommended because reduction in stature is part of normal aging and relative values of gait characteristics do not present a clear picture of actual performance (29).

Reversing gait direction was found to lead to a reduction in stride length in both age groups; however, the reduction was significantly greater in the elderly group. Thus, the stride lengths of young participants in the NBW and FBW were 78% and 70% of the length of the respective forward walks. In contrast, the stride lengths of the older participants in NBW and FBW were reduced to 57% and 51% of their respective forward walks. As the stride lengths of elderly participants in the forward conditions were already significantly shorter than those of young adults, the effect of reversing gait direction on the stride length of elderly participants was most dramatic.

The request to increase gait speed induced a higher gait velocity in both age groups, whether progressing forward or backward. However, the change was found to be more significant in the young group. Researchers have repeatedly shown that increasing forward gait speed is associated with a combined increase in both cadence and stride length (1,29). This increase was observed in the young participants regardless of gait direction. However, among the elderly participants, this was true only for forward ambulation. To accelerate their backward ambulation, the elderly participants relied on increasing cadence and demonstrated an inability to concurrently increase stride length.

Compensatory stepping in all directions is an essential strategy used to prevent falls (24). It has been demonstrated, using destabilizing forces applied backwards at the level of the center of gravity, that the responses of older individuals in comparison to the young, develop more slowly and less vigorously, forcing the older persons to take more than two backward steps to regain their equilibrium (30). In a previous study of elderly persons, single rapid backward stepping, in comparison to forward stepping, was not associated with a decrease in stride length (23). However, the significant reduction in stride length among the elderly participants observed here during backward locomotion, combined with their inability to increase backward stride length even while increasing their gait velocity, seem to indicate that small steps are a dominant characteristic of BW in elderly persons. Furthermore, as demonstrated here and in other studies (2,6,7), FW elderly persons are able to increase their temporal–spatial variables to levels equal to those of young persons progressing at their normal pace. However, they are shown here to be unable to do so in backward ambulation. Because stepping responses are necessary for fall prevention, the difficulties encountered by older persons in taking several consecutive large and rapid steps backward might be a factor contributing to the increase in fall incidence among elderly persons.

Decrease in stride length has been previously noted as the primary contributor to the lower velocity of the forward gait of elderly persons (1,31). In comparing the gait characteristics of young and old persons walking at identical speeds, Kerrigan and colleagues (6) demonstrated that whereas young adults increase hip extension range as gait speed increases, elderly persons demonstrate a reduced hip extension range limiting their stride length at both comfortable and fast speeds. Age-related declines in strength and in the ability to rapidly develop ankle torque have also been demonstrated to be related to changes in the characteristics of forward ambulation of elderly persons (32,33). These biomechanical constraints may similarly limit the ability of elderly persons to walk backwards; these constraints require further investigations.

Although biomechanical constraints probably contribute to the backward gait pattern of elderly persons, the observed temporal–spatial changes may be considered to be components of a general mechanism aimed at maintaining stability. Research has shown that similar changes characteristic of the forward gait in elderly persons serve as stabilizing adaptations related to balance control (34). In young adults, walking backwards has been shown to induce general rigidity of the spine, thereby increasing the effectiveness of head and pelvis stabilization in space (35). Such stabilization makes it easier to extract self-motion information from the optic flow. It has been postulated that, although the dynamic visual cues required to control locomotion equilibrium are equally present in forward and backward ambulation (36), this optic flow does not provide the person progressing backwards with the visual information necessary to anticipate obstacles. Thus, fear of falling may induce not only torso rigidity, but also temporal–spatial changes such as the ones observed here. Lower gait velocity and shorter steps ensure that the center of mass is not shifted far or abruptly from the base of support, while the changes in the gait cycle pattern ensure more time spent in a relatively stable position.

The results of the present study suggest that rehabilitation protocols for elderly persons involving backward locomotion activities should carefully take age-related differences into account. Although taking several steps backward is a functional daily activity used for balance control and for maneuvering in space, BW for long distances is probably a novel task for most individuals. It has been shown with young adults that 12–18 short practice sessions of BW resulted in motor learning, improved skill, and significant reduction in oxygen intake (36,37). Further studies are necessary to examine the ability of elderly persons to improve their BW skills and, even more importantly, to examine the effect of such training on different rehabilitation goals, such as balance control, lower extremity strengthening, and aerobic conditioning.

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