The ability to recover from a fall when balance is lost has been shown to be dependent on the ability to take rapid and long recovery steps (1). Studies showed that older compared with young adults have reduced step length (2), lateral second step following a forward or backward step (3), increased frequency of collisions of the legs during lateral stepping (2), and slower voluntary and compensatory step velocities (4–6). These might be related to the inability to generate lower limb muscle power, which is particularly relevant for explosive and rapid tasks. The impulse is an elementary physical quantity that expresses the force–time relation, which is related to the rapid production of the muscle strength that is needed during the preparatory and swing phases of stepping. Time is a crucial factor in making a force useful in fast situations because force application for long periods of time is not useful. Thus, lower limb muscle power was suggested to be more indicative of the risk of falls than strength in older adults (7).

Another factor potentially limiting an effective and rapid stepping response is the simultaneous performance of an attention-demanding task (8). Dual-task paradigms have been used to simulate real-life situations when the requirement to step rapidly commonly occurs under more complicated circumstances, that is, when cognitive–attention resources are focused elsewhere (e.g., reading street signs or talking while walking). The dual task requires substantially more central information processing (9). The available processing resources are assumed to be limited (10), which may lead to task interference, especially in older adults. In a dual-task situation, older adults make more frequent obstacle contacts when walking (11), take a longer time to recover from instability (12), slow down while walking (13), increase sway in quiet stance (14), and present slower step velocities (4,5) in comparison with single-task situations. Balance-impaired elders take a longer time to regain a stable position when responding to platform perturbations and concurrently performing a cognitive task compared with responding to a postural task alone (15). Recurrent fallers show slower voluntary step execution times compared with nonfallers, in dual-task condition only, with an increased...
risk of fall five times greater in older adults with dual-task step execution time (dual-task condition) compared with single-task stepping (single-task condition). Thus, the purpose of the study was to examine the ability to generate lower limb muscle force and power during rapid voluntary stepping in healthy older and young adults. During the preparatory phase, anticipatory postural adjustments are executed and the actual step is initiated, whereas the swing phase incorporates the actual motor execution of the task when the swinging leg is lifted and physically moves to the target location while the stance leg provides additional forces that push the body in the direction of locomotion. We employed forward and backward stepping tests for a total of 12 step trials. In the single-task condition, participants were instructed to step outside the force plate. Steps were 50–60 cm long; steps that were longer or shorter were extracted for analysis.

Methods

Participants and Procedure

Twelve healthy elderly adults (M = 79.3 ± 4.6 years, range, 71–85 years old) and 19 healthy young adults (M = 27.0 ± 6.0, range, 21–47 years) were recruited from protected retirement homes and from the university population. Elderly participants were included based on the following criteria: no previous neurological or orthopedic disorders, a score greater than 45 on the Berg Balance Scale (30), a Mini-Mental score greater than 24 indicating the absence of serious visual impairment or color blindness, and the ability to ambulate independently (use of cane allowed but not walker). All participants provided informed consent, in accordance with approved procedures by the Boston University Charles River Campus Internal Review Board and Helsinki Committee in Soroka University Medical Center in Beer-Sheva, Israel.

Our sample size estimation was based on a previous work (4) that showed a 238-ms difference in voluntary step time (e.g., foot contact time) between healthy older and younger adults (996 vs 758 ms, respectively) and standard deviation of 223 ms. Using the above numbers for a two-tailed estimate at a significance level of 0.05 and 80% power, a minimum of 12 participants would be required. Furthermore, a higher ratio of young to older adults (19:12) would increase the power of the test.

Participants were instructed to stand upright and barefoot on a force platform (Kistler 9287; Kistler Instrument Corp., Winterthur, Switzerland) and to step as quickly as possible following a tap cue on the heel provided manually by the experimenter; this was always performed with the dominant leg as chosen by the participant (4,5). Because different step sizes could have affected the peak force, peak power, and time to peak force parameters, the participants were instructed to step outside the force plate. Steps were 50–60 cm long; steps that were longer or shorter were extracted from the analysis. Center of pressure (COP) and ground reaction force data during step execution tests were sampled at a frequency of 100 Hz and collected using suitable software (BioWare v.3.24; Kistler Instrument Corp.). A total of six trials (three forward and three backward stepping trials) were conducted for each of the two test conditions (i.e., single- and dual-task conditions), for a total of 12 step trials. In the single-task condition, participants were requested to focus their gaze on an “X” displayed on a large screen placed 3 m in front of them. During the dual-task condition, participants looked at the same screen and performed a modified Stroop test while waiting for the cutaneous cue (4,5). The task consisted of reading colors from a printout showing 25 colored words (five lines of five words), representing color names that were different from the printed colors. For example, the word blue was printed in red ink. The participants were instructed to name the colors of the inks, as quickly as possible, until the end of the procedure. The modified Stroop test (32) was used because the test requires considerable focused attention and few instructions to perform. In addition, it requires only direct verbal responses, does not address memory, and shows relatively small long-term learning effects.

Force platform data were analyzed using custom-made code written in MatLab version 6 (MathWorks Inc., Natick, MA). The following events were extracted from the ground reaction force data (Figure 1): (a) The tap cue was detected as a spike (C) in the anterior–posterior (AP) direction; (b) the step initiation (A) was detected as the first mediolateral
deviation of the COP toward the swing leg; (c) time to Foot-off was defined at the sudden change in the slope of COP toward the stance leg in the mediolateral direction; (d) a successful foot contact or step execution time was determined from the onset of unloading in vertical force seen when the foot of the step leg contacted the ground outside the force platform; (e) preparatory phase was calculated as the time from step initiation to foot-off; (f) swing phase was calculated as the time from foot-off to foot contact; (g) step execution duration was calculated as the time from the tap cue to foot contact. Similar procedures have previously been described in detail (4,5).

An additional code was used to compute the following push-off force–time relations parameters and power during the preparation and swing phases of step execution. (a) AP peak power (Newton meter per second): maximal value in the power–time curve generated in the AP direction within the preparation and swing phases. Power was calculated from
the product of \( F_y(t) \) and \( V_y(t) \). \( F_y(t) \) is the measured force in the direction of locomotion \( Y \) (forward) obtained from the force plate. The acceleration–time curve in the same direction is \( A_y(t) \), which has a profile equivalent to \( F \) because the mass \( m \) is constant during the performance. \( V_y(t) \) is the velocity–time profile obtained from the integral \( \int (t_0 - t_1) \times dt \) (where \( t_0 \) is the time of start of the event and \( t_1 \) is the end of the event where power is calculated); (b) \( \text{AP peak force (Newton)} \): maximal value of force increase in the AP direction, which is the direction of the intended step; (c) \( \text{normalized vertical peak force (body weight units)} \), maximal value of force increase in the vertical direction; (d) \( \text{time to AP peak force (milliseconds)} \): the time to the maximum force after the onset of the preparation and swing phases; (e) \( \text{time to vertical peak force: the time to the maximum force after the onset of the preparation and swing phases (Figure 1).} \)

Statistical Analysis

Shapiro–Wilk test was used to test the normality of the preselected set of variables pooled over the sample population and for both groups independently. Because the variables were not distributed normally to examine the first purpose of the study, we employed Mann–Whitney \( U \) tests to compare between groups (young adults vs older adults) and Wilcoxon’s signed rank test was used to compare between task conditions (single-task condition vs dual-task condition), using SPSS software (SPSS, version 12; SPSS Corp., Chicago, IL). The power-related variables (variables related to the ability of the muscles to exert propulsive power) included AP peak power (Newton meter per second), AP peak force (Newton), normalized vertical peak force (times body weight units), time to AP peak force (milliseconds), and time to vertical peak force (milliseconds). An average of each event across all six trials (three forward and three backward) during single-task and dual-task conditions was used to represent each participant. For each task condition (single task and dual task), a full Bonferroni correction (\( \alpha \)-level .05/5) was used for each of the five nonparametric tests during the preparation and swing phases to achieve an overall significance level of 0.01.

The level of interference was expressed as the average value in dual task divided by single task \( \times 100\% \) within each group. These ratios were normally distributed; thus, Student’s \( t \) test was used to evaluate the interference effect of the dual task. A full Bonferroni correction (\( \alpha \)-level .05/2) for uncorrelated measures was used (\( p \leq .025 \)) for each of the two \( t \) tests (time to AP and time to vertical peak forces) during the preparation and swing phases to achieve an overall significance level of 0.05.

RESULTS

The Effect of Age on Push-Off Force–Time Relations

As seen in Table 1, there were statistically significant differences across almost all step push-off force–time parameters. For example, in single-task condition, the AP peak power and the AP peak force during preparation phase were 36.3% and 22.8% lower for the older adults compared with their young counterparts (62.3 vs 97.9 Nm/s, \( p = .004 \), and 58.5 vs 75.8 N, \( p = .01 \), respectively). During preparation phase, the time to AP peak force and time to vertical peak force were slower for older adults (38.5% and 36.1%, respectively) compared with younger adults (175.1 vs 126.4 ms, \( p = .05 \), and 141.8 vs 104.2 ms, \( p = .008 \), respectively). There were no significant differences in normalized vertical peak force and AP peak power in the swing phase during single-task condition.

Under the dual-task condition, there were no significant differences in the AP peak power between groups. However, AP peak force, time to AP peak force, and time to vertical peak force were significantly different. For example, the time to AP peak force during the preparation and swing phases for older adults were 39.2% and 40.8% slower than those for young adults (234.2 vs 142.5 ms, \( p = .004 \), and 244.8 vs 144.8 ms, \( p = .001 \), respectively).

The Effect of Attention-Demanding Task on Push-Off Force–Time Relations

Preparation phase.—In older adults, the modified Stroop task caused a statistically significant longer time to generate peak forces during the preparation phase (Table 1). Dual-task condition, compared with the single-task condition, showed longer time to AP peak force (25.2%) and time to vertical peak force (24%) in older adults (234.2 vs 175.1 ms, \( p = .003 \), and 186.6 vs 141.8 ms, \( p = .003 \), respectively).

For young individuals, the time to AP peak forces was also significantly delayed during the dual-task condition (142.5 vs 126.4 ms, \( p = .014 \)), although to a lesser extent (11.3%). The time to vertical peak forces during the dual-task condition in the young adult group were 118 versus 104.2 ms in single task, not significantly different (\( p = .18 \)). The peak force and power were not influenced by dual-task condition in both age groups other than normalized vertical peak force in young adults (Table 1).

Swing phase.—For older adults, significant increases in dual-task condition compared with single task for the time to AP peak force are shown in Table 1 (244.8 vs 188.1 ms, \( p = .003 \)) and in vertical peak force (198.6 vs 147.3 ms, \( p = .006 \)) during the swing phase (23.2% and 25.8%, respectively).

For young individuals, the time to AP peak force during the swing phase was 21% longer during dual task than single task (144.8 vs 114.4 ms, \( p = .006 \)), whereas no significant difference was found for time to vertical peak force (102 vs 92.5 ms, \( p = .58 \)). No significant differences in the swing phase were found between task conditions for other variables in both age groups, except for AP peak power and AP peak force for the young adults (Table 1).
The interference effect of an attention-demanding task on time to peak forces (AP and vertical) during the preparation and swing phases is shown in Figure 2; the ratio between dual- and single-task test conditions for the two groups was computed. We computed the time to peak forces because those were the only variables that were significantly different in older adults in both phases. A significant increase between groups in the time to AP peak force was observed during preparation phase for old participants (142%) versus young participants (113%; p = .007). Nonetheless, old and young adults were not statistically different (p = .74) in the time to peak forces at swing phase (129% and 126%, respectively). Similarly, no differences were found for between-group increases in the time to vertical peak force during the preparatory phase in old and young adults (138% and 116%, p = .19, respectively) or during the swing phase (135% and 114%, p = .09, respectively).

### Discussion

This study showed that adding an attention-demanding task delays the ability to generate push-off force rapidly (i.e., time to peak force) after the onset of the preparation and swing phases, whereas in general, peak force and peak power were not affected in older adults (Table 1). Older adults showed a greater delay caused by a concurrent attention-demanding task (~25%) than younger adults (~10%). Furthermore, older adults showed an interference effect caused by a concurrent attention-demanding task (dual/single task ratio), mostly affecting the time to peak force in the direction of locomotion during the preparation phase (Figure 2).

Longer step times due to slower reaction times during dual tasks are well documented (4,5,18–29). Our results provide further evidence of the detrimental effects of diverting attention not only on step reaction times (i.e., step initiation phase) but also on the force–time relation (i.e., the ability to generate force rapidly) during the preparatory and swing phases of dual-task stepping, particularly for older adults (Table 1). Furthermore, it was observed in the present study that older adults frequently stop performing the Stroop task while stepping. These results were taken to support the idea that older adults have limited central information processing resources (i.e., the ability to process information from more than one source) and a deficit in switching between two tasks as the combined demands outweigh available resources, leading to task interference and difficulty in generating force rapidly during dual-task stepping.

**Table 1. Mean Push-Off Force–Time Parameters During Execution of Voluntary Rapid Stepping for Young Adult and Old Adult Participants During Single- and Dual-Task Conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Young Adults</th>
<th>Older Adults</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preparation Phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP peak power (Nm/s)</td>
<td>97.9 ± 7.7</td>
<td>62.3 ± 11.4</td>
</tr>
<tr>
<td>AP peak force (N)</td>
<td>75.8 ± 5.8</td>
<td>58.5 ± 4.6†</td>
</tr>
<tr>
<td>Normalized vertical peak force (TBW)</td>
<td>1.09 ± 0.009</td>
<td>1.06 ± 0.009*</td>
</tr>
<tr>
<td>Time to AP peak force (ms)</td>
<td>126.4 ± 8.7</td>
<td>175.1 ± 18.6</td>
</tr>
<tr>
<td>Time to vertical peak force (ms)</td>
<td>104.2 ± 5.6</td>
<td>141.8 ± 12*</td>
</tr>
<tr>
<td><strong>Swing Phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP peak power (Nm/s)</td>
<td>158.2 ± 22.1†</td>
<td>76.2 ± 18</td>
</tr>
<tr>
<td>AP peak force (N)</td>
<td>73.2 ± 6.3</td>
<td>50.8 ± 8.5*</td>
</tr>
<tr>
<td>Normalized vertical peak force (TBW)</td>
<td>1.02 ± 0.008</td>
<td>1.04 ± 0.009*</td>
</tr>
<tr>
<td>Time to AP peak force (ms)</td>
<td>144.8 ± 16.2‡</td>
<td>234.2 ± 22.1*†</td>
</tr>
<tr>
<td>Time to vertical peak force (ms)</td>
<td>102 ± 11.7</td>
<td>186.6 ± 13.7*†</td>
</tr>
</tbody>
</table>

**Notes:** Values in preparation and swing phases represent averages from six trials ± 1 SEM (average of three forward and three backward stepping trials). AP = anterior–posterior; TBW = times body weight.

* Statistically significant differences between older and young adults (p ≤ .01).
† Statistically significant differences between dual-task conditions and single-task conditions within age groups (p ≤ .01).

**Figure 2.** The interference effect of modified Stroop test on time to peak force in older and young adult participants (dual-task stepping normalized to single-task stepping). The values presented represent ratios in percent ± 1 SD of the average value of all three directions in dual task, the average value of all three directions in single task. Asterisk indicates significant differences between age groups (old vs young; p ≤ .025).
The longer time to generate force during dual-task condition in older adults supports previous trends found in healthy older adults. Rankin and colleagues (27) reported a reduction in the amplitude of the late neuromuscular response of the gastrocnemius to in-place postural response to a platform perturbation in healthy older adults in a dual-task situation. Brauer and colleagues (8) found delayed gastrocnemius onset time and reduced amplitude of swing in the dual-task condition in healthy and balance-impaired older adults during a compensatory stepping response to a perturbation, whereas young adults show only delayed gastrocnemius onset time. These findings suggest that the speed of explosive motor acts (i.e., the ability to generate force rapidly) and cognitive function may both shared and independent brain substrates, indicating that the ability to generate force rapidly is a complex cognitive task that is associated with higher level cognitive function.

Our results suggest that the slower voluntary stepping found in older adults during dual-task condition resulted from bad timing and coordination (i.e., time to peak force) and not due to a reduction of muscle capability (i.e., peak power and peak force). A precise explanation of the neural mechanism underlying the observed task interference is more difficult to give. Although this problem is not the primary concern of the clinical theme of this study, some remarks must be made. The Stroop test requires a different motor response from that needed for step execution. Therefore, it was suggested that the task interference similar to what we reported here is mainly caused by resource competition due to a limited central processing capacity (10). Hausdorff and colleagues (33) found that lower (better) stride time variability was significantly associated with higher (better) scores on the Stroop test. Similarly, when participants were stratified based on their performance on the Stroop test and tests of memory, stride time variability was dependent on the former but not the latter. Holtzer and colleagues (34) found that the Speed/Executive Attention and Memory factors but not Verbal IQ predicted gait velocity in the interference condition.

The Stroop test also requires the processing of visual information. Because vision is involved in postural control (35) and because older adults have an increased tendency to rely on visual information to maintain balance (36), it cannot be denied that part of the interference effect may be due to competitive factors within the uptake or processing of visual information needed to perform the Stroop task and stepping simultaneously. Thus, the interference effect seen here may partially reflect an increased visual dependency in older adults.

This study has several limitations. First, we do not report performance on the concurrent attention-demanding task and the number of mistakes made in the Stroop color word test because participants might focus their attention more strongly on one task domain as opposed to the other (37). For example, older adults might focus their attention on performance of the cognitive attention-demanding task and not to the motor step execution task. However, age-comparative laboratory research has shown that older adults tend to focus their attention more strongly on the sensorimotor task and not on the cognitive domain when both tasks are very resource demanding (38–41). We noted that during the dual-task condition, older adults occasionally stopped reading the color Stroop test while stepping; this suggests a more focused attention on the motor act. This behavior was not seen in the young participants. In fact, the results may suggest that young participants focused their attention more strongly on the Stroop test than on the motor act; thus, a significant decrease in AP peak power (12%) and AP peak force (13%) in dual-task condition compared with single-task condition was found in young adults only. A second limitation is that the data came from a fairly small sample that was drawn from defined, relatively healthy, community-based older adults; these results cannot be generalized to extremely weak or institutionalized elderly persons. Further study should involve larger sample sizes and less healthy populations of older adults. A third limitation might be that the study sample was too small to reveal significant differences during dual-task stepping in the other parameters (e.g., peak force and peak power).

In conclusion, the present study suggests that temporal dynamics of force production (e.g., time to peak force), and not peak force or peak power, are influenced by a secondary attention-demanding task. Longer time to peak force, especially in the direction of locomotion, may represent the inability to recruit muscles fast enough to execute a rapid step and recover from a potential fall when balance is lost during dual-task condition. A secondary task seems to affect the impulse of force; thus, the force is applied for a longer time. Time is a factor that is crucial for making a force useful in such fast situations. Prospective studies are needed to determine if the lower limb force–time relationships during stepping can predict falls in elderly populations. Step training when attention is diverted to another task, and not just strengthening the muscles, may specifically improve speed of dual-task stepping and may decrease the risk of falling.

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