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Age-related differences in lower-limb force–time relation during the push-off in rapid voluntary stepping

I. Melzer [a,d], T. Krasovsky [b], L.I.E. Oddsson [c,d], D.G. Liebermann [e,*]

[a] Department of Physical Therapy, Faculty of Health Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel
[b] Department of Physical and Occupational Therapy, Faculty of Medicine, McGill University, Montreal, Quebec, Canada
[c] Sister Kenny Rehabilitation Institute, Sister Kenny Research Center. Minneapolis, USA
[d] NeuroMuscular Research Center, Boston University, Boston, Ma, USA
[e] Department of Physical Therapy, Sackler Faculty of Medicine, Tel Aviv University, Ramat Aviv, 69978, Israel

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ABSTRACT

Background: This study investigated the force–time relationship during the push-off stage of a rapid voluntary step in young and older healthy adults, to study the assumption that when balance is lost a quick step may preserve stability. The ability to achieve peak propulsive force within a short time is critical for the performance of such a quick powerful step. We hypothesized that older adults would achieve peak force and power in significantly longer times compared to young people, particularly during the push-off preparatory phase.

Methods: Fifteen young and 15 older volunteers performed rapid forward steps while standing on a force platform. Absolute anteroposterior and body weight normalized vertical forces during the push-off in the preparation and swing phases were used to determine time to peak and peak force, and step power. Two-way analyses of variance ('Group' [young–older] by 'Phase' [preparation-swing]) were used to assess our hypothesis ($P \leq 0.05$).

Findings: Older people exerted lower peak forces (anteroposterior and vertical) than young adults, but not necessarily lower peak power. More significantly, they showed a longer time to peak force, particularly in the vertical direction during the preparation phase.

Interpretations: Older adults generate propulsive forces slowly and reach lower magnitudes, mainly during step preparation. The time to achieve a peak force and power, rather than its actual magnitude, may account for failures in quickly performing a preventive action. Such delay may be associated with the inability to react and recruit muscles quickly. Thus, training elderly to step fast in response to relevant cues may be beneficial in the prevention of falls.

1. Introduction

Muscle strength is an important determinant of functional performances such as getting up from a chair, climbing stairs, and walking (Bassey and Short, 1990; Ikezoe et al., 1997). It is well documented that lower-limb muscle strength peaks around the age of 30 and decreases at a rate of 1–2% per year after the fifth decade of life (Borges, 1989; Freedson et al., 1993). Muscle quality or specific tension (i.e., maximal voluntary strength per unit of cross-sectional area) is an assumed indicator of both muscle strength and contractile velocity (De Vito et al., 1998; Krivickas et al., 2001), which indeed also decrease with age (Doherty, 2004). Because the marked increase in the incidence of falls in older adults (Tinetti et al., 1988) coincides with the progressive reduction in lower-limb muscle mass, strength has been considered a primary factor associated with falling. Yet, the age-related decline in muscle power is greater (3–4% per year) than the decline in muscle strength (Bassey and Short, 1990; Bean et al., 2003; Skelton et al., 1994). Thus, muscle power has also been considered a major factor related to increase in the risk of falling in older adults (Skelton et al., 2002). However, some studies have shown minimal or no differences in lower-limb muscle strength between fallers and non-fallers (Wolfson et al., 1993; Judge et al., 1994). That is, the evidence for the suggested relation between muscle strength or muscle power to falling in older adults is controversial.

There could be several reasons for such a controversy. For example, muscle strength in older adults has been assessed using dynamometric techniques (Judge et al., 1994; Melzer et al., 2000), while neglecting important functional aspects of muscle capability in real-life situations (e.g., the ability to step rapidly). Another controversy relates to differences in the definition of power under different perspectives. Mechanical and metabolic definitions of power (or energy; i.e., the integral of power) are often assumed to be

* Corresponding author.
E-mail address: dlieberm@post.tau.ac.il (D.G. Liebermann).

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synonymous, although the relation between the two is ambiguous. For example, different types of fast walking or running (in humans or animals) are meant to maintain the vertical speed of the center of mass near zero and the speed in the direction of locomotion nearly constant (i.e., near zero vertical and horizontal accelerations). Indeed, this should optimize mechanical energy. However, it is known that mechanical parameters associated with power or energy do not strongly correlate with metabolic cost under different speeds of locomotion (e.g., see review by McMahon, 1984). In this regard, older people may show decreased ability to produce metabolic power or energy in a continuous gait, but not necessarily decrease in mechanical power as expressed in a single discrete stepping action that may prevent a fall. Power in the last case strongly depends on the ability to release energy fast enough with the right timing.

In the current study, we adopt a mechanical definition where forward stepping power results from the propulsive tangential force and velocity. We argue that in older adults it is not the magnitude of the exerted power per se but the time evolution of the force generation that may be associated with the ability to react quickly and avoid falling. It should be noted that such a suggestion is compatible with previous findings using similar stepping paradigms, which showed slow anticipation and stepping reaction times in older adults (Melzer et al., 2007a).

Thus, the general aim of the current study was to verify whether propulsive force and power differ in young and older adults during the push-off in a rapid step, and in what aspects they differ. In particular, we were interested in the relationship between the generation of propulsive force and the time of force application because this relationship may reflect the ability to generate muscle power (Liebermann and Katz, 2003). We assumed that delays in generating forces during the push-off stage are critical for fast forward stepping actions that may prevent falls in older adults. This assumption is partially supported by Pijnappels et al. (2005), who showed delays in the onset of knee-movement generation in the support limb in older fallers during the recovery after tripping, accompanied by a lower peak ankle-moment during push-off reactions.

Specifically, we examined age-related differences in push-off ability from force–time data obtained in rapid voluntary step executions based on the assumption that the ability to perform a rapid step may be important for preventing a fall during locomotion (Madigan and Lloyd, 2005). Previous work showed longer step execution times in older compared to young adults (Bean et al., 2003; Melzer and Oddsson, 2004; Melzer et al., 2007a, b). In this study, we hypothesized that older adults would indeed achieve lower force and power magnitudes compared with young adults during the push-off phase of a forward step execution. Such differences may be attributed to the decreased ability to reach peak force values in short time intervals. Thus, we further hypothesized that older people would achieve peak force and power in significantly longer times compared to young people, during the preparatory and swing phases of the push-off. Lastly, we hypothesized that such differences would be observed in the preparatory phase of the push-off rather than in the swing phase.

2. Method

2.1. Participants and procedures

Fifteen healthy older adult (9 males) and 15 young (8 males) volunteers were recruited for the study. Older participants were included based on the following criteria: no previous neurological or orthopedic disorders, a score greater than 45 on the Berg Balance Scale (Berg et al., 1992), a Mini-Mental Score greater than 24 indicating the absence of moderate to severe dementia (Folstein et al., 1975), and the ability to ambulate independently. The use of a cane was allowed but not a walker. Descriptive data for our samples of healthy young and older individuals are shown in Table 1.

All participants provided informed consent, in accordance with approved procedures by the Ethics Internal Review Board on human and animal experimentations of the relevant institutions.

2.2. Instrumentation and experimental design

A 40 cm × 60 cm Kistler 9287BA multi-component force platform with built-in charge amplifiers (Kistler Instrument Corp., Winterthur, Switzerland) was mounted in a community center to measure ground reaction force data. The 3D force data were sampled at a frequency of 100 Hz and stored for off-line analysis. The collected data included shear (ML = mediolateral and AP = anteroposterior; i.e., forces Fx and Fy, respectively) and vertical (Fz) force components. The Fz data also enabled the off-line computation of the center of pressure (COP) during each step execution trial.

The participants were instructed to adopt a standardized stance with their feet abducted 10°, and their heels separated mediolaterally by 6 cm. The repeatability of foot position was controlled through the use of a rigid template that forced the feet into the proper position at the start of each trial. The template was removed prior to the start of the data collection. The stepping foot was the same for all trials and chosen by the individual. Participants performed three familiarization trials before the initiation of the data collection. Before the initiation of the test, they were told to "stand evenly on both feet and to step as quickly as possible following a tap on the heel of the stepping foot". Because different step sizes could have affected the peak force, peak power, and time to peak force parameters, participants were instructed to step within a strip marked on the ground (in the range of 50–60 cm) outside the force plate limits (longer or shorter steps were not considered).

2.3. Analysis and dependent measures

Force data were analyzed using custom-made routines written in MatLab (version R2008b, MathWorks, Natick, MA, USA). For each trial, the following parameters were obtained: (1) *tap-cue time*, defined as the zero-time where the first significant rise of force occurred in the AP direction (i.e., the direction of the tap). This event was automatically detected by searching for the first sample where the AP value of force exceeded for the first time 10 × SD of baseline data collected while standing for 1 s; (2) *step-initiation time*, defined by the first sample where the change in the COP in the ML direction exceeded 2 × SD of the baseline value for at least two consecutive samples; (3) *foot-off time*, defined as the first sample after peak absolute COP (i.e., $|COP| = \sqrt{COP_X^2 + COP_Y^2}$) remained stable (i.e., if COP returned to its baseline value for two consecutive samples); (4) *foot-contact time*, detected when the vertical force Fz first decreased by at least 10 × SD of the mean Fz; (5) *preparatory phase duration*, calculated as the time from step initiation to the foot-off time; (6) *the swing phase duration*, calculated as the time from foot-off to foot-contact. Force–time data were captured and converted to ASCII files

Table 1
Descriptive statistics (mean (SD) and range) for the sample of 15 young and 15 older adults.

Groups	Young		Older	
Variables	Mean (SD)	Range	Mean (SD)	Range
Age (years)	27.0 (6.0)	21–47	79.3 (4.6)	71–85
Weight (kg)	65.5 (10.0)	54–87	68.0 (12.3)	59–101
Height (cm)	169.4 (7.0)	160–183	158.8 (8.3)	142–178
BMI (kg/m^2)	22.9 (2.2)	20.5–27.5	26.9 (4.4)	18.0–40.0