Published in final edited form as:

Gait Posture. 2014 January ; 39(1): . doi:10.1016/j.gaitpost.2013.06.012.

Advanced age and the mechanics of uphill walking: a joint-level, inverse dynamic analysis

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Abstract

We sought to gain insight into age-related muscular limitations that may restrict the uphill walking ability of old adults. We hypothesized that: 1) old adults would exhibit smaller peak ankle joint kinetics and larger peak hip joint kinetics than young adults during both level and uphill walking and 2) these age-related differences in ankle and hip joint kinetics would be greatest during uphill vs. level walking. We quantified the sagittal plane ankle, knee, and hip joint kinetics of 10 old adults (mean $\pm$ SD, age: 72 ± 5 yrs) and 8 young adults (age: 27 ± 5 yrs) walking at 1.25 m/s on a dual-belt, force-measuring treadmill at four grades (0° , $+3^\circ$, $+6^\circ$, $+9^\circ$). As hypothesized, old adults walked with smaller peak ankle joint kinetics (e.g., power generation: -18% at $+9^\circ$) and larger peak hip joint kinetics (e.g., power generation: $+119\%$ at $+9^\circ$) than young adults, most evident during the late stance phase of both level and uphill conditions. Old adults performed two to three times more single support positive work than young adults via muscles crossing the knee. In partial support of our second hypothesis, the age-related reduction in peak ankle joint moments was greater during uphill (-0.41 Nm/kg) vs. level (-0.30 Nm/kg) walking. However, old adults that exhibited reduced propulsive ankle function during level walking could perform 44% more trailing leg positive ankle joint work to walk uphill. Our findings indicate that maintaining ankle power generation and trailing leg propulsive function should be the primary focus of “prehabilitation” strategies for old adults to preserve their uphill walking ability.

Keywords

aging; elderly; locomotion; kinetics; mechanics; incline; prehabilitation

INTRODUCTION

The biomechanical demands of uphill walking can be challenging for community-dwelling old adults. However, very little is known about how old adults walk uphill. We know that advanced age (65+ years) brings unfavorable changes in ground reaction forces (GRFs), mechanical work, and leg muscle recruitment during both level (1–5) and uphill walking (1, 6). While these measures have been valuable and informative, they offer only indirect

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to disclose.

insight into the muscular limitations of old adults walking uphill. The next step is to compare the kinetics (moments and powers) of old and young adults at each leg joint to more precisely identify biomechanical factors that may contribute to impaired uphill walking ability with age. In this study, we used motion analysis techniques and an inverse dynamics approach to provide joint-level insights into age-related muscular limitations that may restrict the uphill walking ability of old adults.

Numerous studies have described the joint kinetics of old vs. young adults walking over level ground (7–13). These studies reveal that old adults exhibit a distal to proximal redistribution of mechanical power production, from muscles acting across the ankle to muscles acting across the hip. Even healthy and active old adults generate up to 29% less ankle power compared to young adults (7–11, 13). Reduced ankle joint kinetics in old adults are accompanied by an increase in hip extensor moments and power generation during early stance (8, 11, 13) and/or an increase in hip flexor moments and power generation during push-off (7, 9, 10). Explanations for the distal to proximal redistribution of joint kinetics include underlying neural changes with age and/or a compensation for the propulsive deficits of ankle extensor muscles.

Uphill walking places increased demands on the leg muscles of old adults which could exacerbate age-related changes in leg joint kinetics. We recently demonstrated that overall trailing leg propulsive function is compromised in old vs. young adults during uphill walking. Old adults walked with smaller peak propulsive GRFs and trailing leg positive center of mass (CoM) work rates than young adults (1). Old adults compensated by performing greater positive CoM work during the single support phase, which is consistent with their disproportionate recruitment of proximal vs. distal leg muscles. Indeed, old adults exhibit smaller increases in ankle extensor muscle activities with steeper uphill grade and greater recruitment of their gluteus maximus (a hip extensor muscle) than young adults during both level and uphill walking (6). Further, Lay et al. (2006) showed that for young adults, the greatest increases in joint kinetics during uphill vs. level walking occur at the hip. Accordingly, we have shown that due to the combined effects of age and uphill grade, old adults approach the maximum EMG-based isometric capacity of their gluteus maximus during steeper uphill walking (6). As walking performance declines with age (14), a greater reliance on proximal joint kinetics may be an inadequate strategy to meet the propulsive demands of uphill walking.

In this study, we quantified the sagittal plane ankle, knee, and hip joint moments and powers in healthy old and young adults during level and uphill walking. We hypothesized that: 1) old adults would exhibit smaller peak ankle joint kinetics and larger peak hip joint kinetics than young adults during both level and uphill walking and 2) these age-related differences in ankle and hip joint kinetics would be greatest during uphill vs. level walking.

METHODS

Subjects

We analyzed the gait of 10 old adults (6F/4M, mean $\pm$ SD, age: 72 ± 5 yrs, height: 1.70 ± 0.10 m, mass: 65.0 ± 13.3 kg) and 8 young adults (4F/4M, age: 27 ± 5 yrs, height: 1.76 ± 0.07 m, mass: 71.5 ± 8.44 kg) who were healthy and exercised regularly. Prior to participating, subjects completed a health questionnaire based upon recommendations of the American College of Sports Medicine (15). We excluded subjects based upon the following: BMI ≥ 30 , sedentary lifestyle, first degree family history of coronary artery disease, cigarette smoking, high blood pressure, high cholesterol, diabetes or prediabetes, orthopedic or neurological condition, or taking medication that causes dizziness. All subjects gave written informed consent as per the University of Colorado Institutional Review Board.

Experimental Procedures

Subjects completed four experimental sessions which each involved walking for 2 min at 1.25 m/s on a dual-belt, force-measuring treadmill (16). Subjects began each session by walking for 5 min on a conventional, level treadmill (model 18–60, Quinton Instruments, Seattle, WA) to allow their movement patterns to stabilize. Subjects then walked on the force treadmill on the level during session 1 and uphill at one of three grades (3°, 6°, 9°; i.e., 5.2%, 10.5%, 15.7%) during sessions 2–4. For context, the Americans with Disabilities Act permits uphill walking ramps of 4.8° (i.e., 8.3%). For uphill walking trials, we mounted each side of the treadmill on separate, custom-made aluminum wedges as described in earlier studies (Figure 1) (17). Subjects completed the experimental sessions on separate days and in the same condition order due to the lengthy process of changing the treadmill grade. A force platform (model ZBP-7124- 6-4000, Advanced Mechanical Technology, Inc., Watertown, MA) mounted under one side of the treadmill recorded the right leg three-dimensional ground reaction forces and moments at 1000 Hz during the last 30 s of each trial.

We placed 15 retro-reflective markers on each subject's skin/shoes corresponding to the following anatomical landmarks: anterior superior iliac spines, sacrum, greater trochanters, lateral femoral condyles, tibial tuberosities, lateral malleoli, posterior calcanei, and lateral fifth metatarsal heads. An 8-camera motion analysis system (Motion Analysis Corp, Santa Rosa, CA) captured the three-dimensional marker positions at 100 Hz in synchrony with the GRF data. We also recorded anthropometrics including height, body mass, and leg segment lengths and circumferences.

Data Analysis

We used a custom Matlab (Mathworks, Inc, Natick, MA) script based upon analysis methods described by Vaughan et al. (1999) to calculate the sagittal plane leg joint kinematics and kinetics for each subject over 15 consecutive strides. Briefly, marker position data (low-pass filtered at 10 Hz) defined orthogonal *uvw* reference systems for each segment, which we combined with anthropometrics to estimate the joint center locations and each segment's CoM (18). We then embedded an internal *xyz* reference system at each segment's CoM which defined that segment's position and orientation relative to the laboratory reference frame. We used these internal reference systems to calculate the anatomical joint angles, segment Euler angles, and segment angular velocities and accelerations. We combined those kinematic data with low-pass (20 Hz) filtered and down-sampled force plate data to calculate our primary measures (sagittal plane ankle, knee, and hip joint moments and powers) using a standard inverse dynamics procedure (18). By convention, we report net internal joint flexion and extension moments. We determined local maxima and minima from subjects' average joint kinematic (entire gait cycle) and kinetic (stance phase only) profiles for comparison. In a secondary analysis, we integrated the joint power curves with respect to time to calculate the net positive work performed by muscles crossing the ankle, knee, and hip. We performed these integrations over time periods corresponding to the double and single support phases, identified using the individual leg GRF measurements. Specifically, we analyzed the primary sources of positive work: the trailing leg during double support and the stance leg during single support. An analysis of variance (ANOVA) for repeated measures tested for significant main effects of and interactions between age and grade with a $p < 0.05$ criterion.

RESULTS

For simplicity, we report age-related differences for level walking and uphill walking at 9°, summarized in Figures 2–4. All curves are normalized to the gait cycle (right heel-strike to

right heel-strike), noting that step duration tended to be 10% shorter for old vs. young adults during uphill walking ($p=0.051$) largely due to a shorter single support phase. We found no differences in sagittal plane joint kinematics between old and young adults (Figure 2).

A significant interaction revealed that only young adults increased their peak ankle extensor moments during uphill vs. level walking ($p=0.003$). Also at the ankle, old adults produced $20\pm13\%$ (mean $\pm$ SE) (level) and $25\pm10\%$ (uphill) smaller peak extensor moments and generated $25\pm19\%$ (level) and $18\pm16\%$ (uphill) less peak power than young adults ($p=0.001$ and $p=0.014$, respectively) (Figures 3 and 4).

At the knee, old (O) adults produced extensor moments during the late stance phase of both level and uphill walking which differed significantly from the flexor moments produced by young (Y) adults (O vs. Y; level: 0.24 ± 0.11 vs. -0.06 ± 0.08 Nm/kg; uphill: 0.05 ± 0.07 vs. -0.31 ± 0.08 Nm/kg, $p=0.011$) (Figure 3).

At the hip, old adults generated $148\pm98\%$ (level) and $119\pm86\%$ (uphill) more peak hip power than young adults immediately preceding toe-off ($p=0.013$) (Figure 4). Old adults also produced $63\pm45\%$ (level) and $110\pm67\%$ (uphill) larger peak flexor moments and absorbed $128\pm77\%$ (level) and $246\pm113\%$ (uphill) more peak power than young adults during mid- to late-stance ($p=0.007$ and $p=0.003$, respectively) (Figures 3 and 4).

Old and young adults walked at the same speed and grades which required that they perform the same overall net rate of mechanical work for each condition. However, old and young adults differed significantly in which muscles they used to perform this work and in their relative timing (double vs. single support) (Figure 5). During double support, old adults performed $317\pm165\%$ (level) and $119\pm112\%$ (uphill) more trailing leg positive work than young adults using muscles crossing the hip ($p=0.012$) (Figure 5). However, this was not enough to compensate for the reduced contribution from muscles crossing the trailing leg knee and ankle joints. Thus, old adults tended to perform 20% (level) and 16% (uphill) less total double support trailing leg positive joint work than young adults ($p=0.051$), despite no difference in double support duration ($p=0.422$). During single support, old adults performed two to three times more positive work than young adults using muscles crossing the knee (O vs. Y; level: 0.08 ± 0.02 vs. 0.04 ± 0.01 J/kg; uphill: 0.14 ± 0.03 vs. 0.05 ± 0.02 J/kg, $p=0.027$) (Figure 5). In contrast, old adults performed $75\pm59\%$ (level) and $70\pm23\%$ (uphill) less single support positive work per step than young adults using muscles crossing the hip ($p<0.001$).

DISCUSSION

In this study, we quantified the effects of advanced age on sagittal plane ankle, knee, and hip joint moments and powers during level and uphill walking. We found general agreement between our reported joint kinetics for young adults during uphill vs. level walking and previously published results (19–22). Consistent with our first hypothesis, old adults walked with less vigorous peak ankle joint kinetics and more vigorous peak hip joint kinetics than young adults, evident during the late stance phase of both level and uphill conditions. In partial support of our second hypothesis, the age-related reduction in peak ankle joint moments was greater during uphill (0.41 Nm/kg) vs. level (0.30 Nm/kg) walking. Other age-related differences in peak joint moments and powers were consistent between level and uphill walking. Our findings reveal potential muscular limitations, most notably at the ankle, that may restrict the uphill walking ability of old adults.

Trailing leg ankle power during push-off propels the body's CoM forward and initiates leg swing (23). We found that old adults generated significantly less ankle power and significantly more hip power than young adults during the push-off phase of both level and uphill walking. Other authors (9, 24) have suggested that old adults compensate for reduced

ankle power generation by relying more on hip flexor muscles to initiate leg swing. While consistent with that interpretation, our findings indicate that the trailing leg propulsive deficits of old adults persist despite their generating greater hip power than young adults during push-off. For example, old adults performed 16% less total positive trailing leg *joint work* than young adults during uphill walking. This difference is consistent with our prior study (1) in which we showed that old adults exert 21% smaller propulsive GRFs and perform 26% less trailing leg *CoM work* than young adults to walk uphill. While we had previously learned that old adults walk uphill with reduced whole-body propulsive function, we had no quantitative evidence of their joint-level muscular limitations (1). Our current findings reveal that reduced ankle power generation during push-off may ultimately impair the walking ability of old adults, particularly at steeper uphill grades.

Based on their ability to walk uphill, we previously proposed that old adults have an underutilized propulsive reserve available during level walking (6). In support of this idea, here we found that old adults performed 44% more positive work via trailing leg muscles crossing the ankle during uphill vs. level walking. If old adults can increase propulsive ankle function to walk uphill, why don't they utilize this capacity during level walking? One possibility is that the greater hip flexor moments produced by old adults act to reduce the force exerted on the ground during late-stance and thus preclude their ankle extensors from generating as much power as young adults. Hip flexor moments during walking are produced via passive structures resisting hip extension (e.g., ligaments) and the recruitment of hip flexor muscles (10, 13, 25). Moreover, we previously described that a shift from feedback to feedforward neural control with age could in part bring the greater recruitment of hip muscles observed in old adults (6). Thus, a loss of hip flexibility and/or a greater recruitment of hip flexor muscles could thereby reduce ankle power generation in old adults. Another possibility is that these characteristic propulsive mechanics represent a purposeful adaptation which acts to enhance other features of gait in old adults (e.g., improved balance).

The adverse effects of distal muscle weakness on trailing leg propulsion may be most clearly exposed at steeper uphill grades. Indeed, in contrast to young adults, old adults did not increase their peak ankle extensor moments to walk uphill. Consistent with this finding, old adults exhibit smaller increases in ankle extensor muscle activities than young adults during uphill vs. level walking (6). Distal muscle weakness may be one factor limiting the ankle extensor moments produced by old adults at steeper uphill grades. Such an effect could originate from a decrease in the force-generating capacity of the ankle extensor muscles (26) and/or from adverse changes in their contractile state (force-length and force-velocity relationships) (27) with age.

We previously found that old adults perform positive *CoM work* during single support at a faster rate than young adults, thereby compensating for overall trailing leg propulsive deficits (1). Although the old adults in the present study performed the same total amount of single support *joint work* per step as young adults during uphill walking, they did so over a shorter time duration. Based on our EMG data alone (6), we suspected that greater concentric actions of hip extensor muscles (e.g., gluteus maximus) in old vs. young adults would account for the greater rate of positive work performed during single support. Instead, we found here that old adults perform 109% (level) and 165% (uphill) greater positive work than young adults during single support via muscles acting across the knee. Thus, together with our prior study (1), this implies that old adults walk a given uphill distance by performing more single support positive work than young adults and do so using knee extensor muscles.

The greatest increases in joint kinetics during uphill vs. level walking occurred at the hip during the early stance phase for both old and young adults. During this phase, peak hip extension moments and peak hip power generation did not statistically differ between old and young adults, which is consistent with several earlier studies of level walking (7, 9, 10). However, because hip power generation ended earlier in the gait cycle for old adults, we found that they performed less hip joint positive work than young adults during single support (Figures 4, 5). In young adults walking uphill, single support hip joint positive work is performed largely by hip extensor muscles (20, 21, 28, 29) and we know that old adults approach the maximum EMG-based isometric capacity of their gluteus maximus (a hip extensor) at steep uphill grades (6). Thus, old adults may perform less hip joint positive work than young adults to operate within their maximum capabilities, particularly during uphill walking.

There are several limitations of this study. First, we replaced the marker set at the start of each session which occurred on separate days due to the lengthy process of changing treadmill grade. However, the same research assistant placed the markers for each subject and errors introduced by marker placement would not be systematic across group or condition. Second, our findings are limited to the active and fit old adults that we recruited. We suspect that sedentary and/or frail old adults with more advanced sarcopenia and muscle weakness would have been unable to complete this study. Finally, unlike previous studies (7–11, 13), we compared old and young adults walking on a treadmill. Compared to overground walking, level treadmill walking in old adults is accompanied by small, but statistically significant changes in hip joint kinetics including smaller hip extensor moments (30). It is unclear if the biomechanics of uphill walking on a treadmill differ from those measured overground for old or young adults.

In this study, we have shown that advanced age brings joint-level kinetic changes that may eventually restrict the uphill walking ability of old adults. Old adults exhibit impaired trailing leg propulsive function during uphill walking largely because they generate significantly less ankle power than young adults during push-off. Less vigorous ankle joint kinetics in old adults during level and uphill walking are accompanied by two more proximal increases: 1) greater hip power than young adults during push-off to initiate leg swing and 2) greater positive work during single support via muscles acting across the knee (i.e., quadriceps). In our opinion, interventions to preserve the uphill walking ability of old adults should focus on the source of their walking impairments rather than observed compensations. Thus, our findings indicate that maintaining ankle power generation and trailing leg propulsive function with age should be the primary focus of “prehabilitation” strategies for old adults.

Acknowledgments

We thank Dr. Alaa Ahmed for her help in developing the inverse dynamics script used in our analysis. We also thank Alyse Kehler and Lauren MacDonald for their help with subject recruitment and data collection and analysis. Supported by a grant from NIH (5T32AG000279) and a student Grant-in-Aid from the American Society of Biomechanics.

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Figure 1.

Dual-belt force-measuring treadmill mounted at 9°. A force platform mounted under treadmill TM1 recorded the perpendicular, parallel, and lateral (not shown) components of the ground reaction force (GRF) from a single leg.

Figure 2.

Sagittal plane ankle, knee, and hip joint angles of old and young adults during level (solid lines) and uphill (+9°, dashed lines) walking plotted over an averaged gait cycle (0–100%). Vertical lines indicate toe-off. Greater than (>) indicates a significant main effect of grade ($p < 0.05$). We found no statistically significant differences in any sagittal plane joint kinematic maxima or minima between old and young adults.

Figure 3.

Sagittal plane ankle, knee, and hip joint moments of old and young adults during level (solid lines) and uphill (+9°, dashed lines) walking plotted over an averaged gait cycle (0–100%). Vertical lines indicate toe-off. Single asterisks (*) indicate a significant difference between old and young adults and greater than (>) indicates a significant main effect of grade ($p < 0.05$). Pound (#) indicates that the peak ankle extensor moment increased during uphill vs. level walking in young, but not old adults (interaction, $p < 0.05$). Only stance phase local maxima and minima identified by a single asterisk (*) differed significantly between old and young adults.

Figure 4.

Sagittal plane ankle, knee, and hip joint powers of old and young adults during level (solid lines) and uphill (+9°, dashed lines) walking plotted over an averaged gait cycle (0–100%). Vertical lines indicate toe-off. Single asterisks (*) indicate a significant difference between old and young adults and greater than (>) indicates a significant main effect of grade ($p < 0.05$). Only stance phase local maxima and minima identified by a single asterisk (*) differed significantly between old and young adults.

A.

B.

Figure 5.

Average (SE) joint mechanical work per step performed during (A) double (trailing leg) and (B) single support in old and young adults. Old adults tended to perform less total trailing leg positive work than young adults ($p=0.051$), but performed more trailing leg positive work than young adults using muscles acting across the hip ($p=0.012$). The total joint work performed during single support was not significantly different between old and young adults ($p=0.593$). However, old adults performed more single support positive work than young adults via muscles acting across the knee ($p=0.027$) and less via muscles acting across the hip ($p<0.001$). We did not quantify the double support positive work performed by

muscles acting across the ankle, knee, and hip joints of the leading leg, which contribute significantly less to forward propulsion than those of the trailing leg (17).