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Ankle power biofeedback attenuates the distal-to-proximal redistribution in older adults

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ABSTRACT

Background: Compared to young adults, older adults walk slower, with shorter strides, and with a characteristic decrease in ankle power output. Seemingly in response, older adults rely more than young on hip power output, a phenomenon known as a distal-to-proximal redistribution. Nevertheless, older adults can increase ankle power to walk faster or uphill, revealing a translationally important gap in our understanding.

Research question: Our purpose was to implement a novel ankle power biofeedback paradigm to encourage favorable biomechanical adaptations (i.e. reverse the distal-redistribution) during habitual speed walking in older adults.

Methods: 10 healthy older adults walked at their preferred speeds while real-time visual biofeedback provided target increases and decreases of 10 and 20% different from preferred ankle power. We evaluated the effect of changes in ankle power on joint kinetics, kinematics, and propulsive ground reaction forces. Pre and post overground walking speed assessments evaluated the effect of increased ankle power recall on walking speed.

Results: Biofeedback systematically elicited changes in ankle power; increasing and decreasing ankle power by 14% and 17% when targeting ± 20% different from preferred, respectively. We observed a significant negative correlation between ankle power and hip extensor work. Older adults relied more heavily on changes in ankle angular velocity than ankle moment to modulate ankle power. Lastly, older adults walked almost 11% faster when recalling increased ankle power overground.

Significance: Older adults are capable of increasing ankle power through targeted ankle power biofeedback – effects that are accompanied by diminished hip power output and attenuation of the distal-to-proximal redistribution. The associated increase in preferred walking speed during recall suggests a functional benefit to increased ankle power output via transfer to overground walking. Further, our mechanistic insights allude to translational success using ankle angular velocity as a surrogate to modulate ankle power through biofeedback.

1. Introduction

Compared to young adults, older adults walk slower, with shorter strides, and with a characteristic decrease in push-off intensity. These changes stem in part from reduced positive ankle power output during terminal stance, the peak of which we define herein as P_A, which in turn diminishes propulsive ground reaction forces (F_P) [1]. Seemingly in response, older adults rely more than young on hip power output, a phenomenon known as a distal-to-proximal redistribution. An insufficient push-off from the ankle requires greater hip extensor power output to redirect and accelerate the body's center of mass [1]. Hip extensor muscles are comprised of long fascicles with short tendons which may be less economical to operate than the relatively short fascicles and long, series elastic tendon of the plantarflexors. This may, at least in part, explain why older adults consume metabolic energy at a faster rate than young adults walking at the same speed [2]. It is thus translationally important to develop novel techniques to restore ankle push-off performance in older adults.

As an important first step, we previously attempted to enhance push-off intensity in older adults using biofeedback to increase propulsive forces. This biofeedback paradigm effectively increased peak propulsive forces, and older adults responded with longer steps, increased trailing limb extension, and decreased ipsilateral hip flexor power generation during push-off [3]. While these changes may be beneficial, this biofeedback paradigm was unable to elicit changes in P_A. One interpretation of this outcome is that reduced P_A could be a genuine functionally limiting impairment in elderly gait that older adults are unable to overcome. Alternatively, increasing P_A may not be

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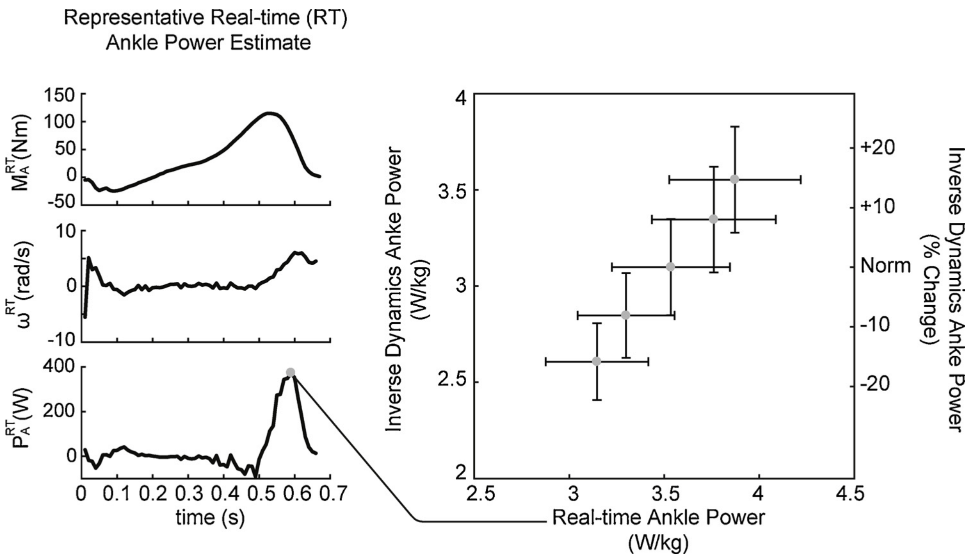

Fig. 1. Real-time inverse dynamics and ankle power biofeedback paradigm. A surrogate inverse dynamic model of the shank and foot estimated, in real-time, the instantaneous ankle moment and angular velocity, which we then used to estimate step-by-step peak ankle power (P_A). Representative raw data from a single stance phase shown. Grey dots represent group mean (± SD; n = 10) of the real-time estimate of P_A versus the post-processed full inverse dynamic estimate of P_A alongside their respective % changes. These data demonstrate the efficacy of the biofeedback paradigm in eliciting predictable changes in P_A.

a prerequisite for increasing peak propulsive forces. Indeed, young adult subjects also responded to the same biofeedback paradigm without increasing P_A. Accordingly, we posit that therapies that more directly target age-related deficits in P_A are needed to improve ankle push-off in older adults.

Unfortunately, sarcopenia and a loss of muscle strength with aging may place functional limitations on P_A that may be difficult to overcome. Accordingly, resistance training to improve muscle strength is frequently prescribed for older adults to improve muscle mechanical output and thus walking speed. While these studies report increased muscle strength and improved fast walking speed (FWS), they tend not to affect habitual walking performance (i.e. preferred walking speed; PWS) or gait biomechanics (e.g., distal-to-proximal distribution) [4–6]. Nevertheless, compared to that normally adopted at their preferred speed, older adults can increase P_A to walk faster or uphill, revealing a translationally important gap in our understanding. Ultimately, this suggests that older adults retain the potential to better utilize their capacity to enhance P_A given more targeted training and guidance.

Our purpose was to implement a novel ankle power biofeedback paradigm based on real-time inverse dynamics to encourage favorable biomechanical adaptations during habitual speed walking in older adults. We tested the primary hypothesis that real-time ankle power biofeedback during walking can successfully augment P_A in older adults. We also hypothesized that: (*i*) targeting increases in P_A would alleviate mechanical power demands at the hip while (*ii*) targeting decreases in P_A would increase mechanical power demands at the hip. We further hypothesized that subjects would increase preferred but not fast overground walking speed when recalling targeted increases in P_A. Lastly, we evaluated the mechanisms used to modulate P_A with biofeedback to inform more practical translational efforts to enhance push-off intensity.

2. Methods

2.1. Participants

We recruited 10 healthy older adults ranging from 69 to 85 years (mean ± SD; age: 74.8 ± 5.4 years, height: 1.71 ± 0.10 m, mass: 62.6 ± 13.2 kg, 7 females) to participate. We also include reference data from 9 young adults (age: 25.1 ± 5.6 years, height: 1.76 ± 0.06 m, mass: 72.0 ± 7.1 kg, 5 females). Exclusion criteria were: BMI ≥ 30, lower extremity fracture during previous 6 months, neurological disorder affecting the legs, pain during walking, leg prosthesis, and requiring an assistive aid for ambulation. On average, our older adult subjects performed vigorous activity 1.6 ± 2.2 times a week, moderate activity 4.2 ± 1.5 times a week, and light activity 4.0 ± 2.8 times a week. All subjects provided written, informed consent according to the University of North Carolina Institutional Review Board.

2.2. Measurements

We assessed older and young adults' PWS and FWS as the average time (3 repetitions) to traverse the middle 3 m of a 10 m walkway using a photo cell timing system (BTS, Draper, UT, USA). A motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA) then recorded the 3-dimensional trajectories of markers placed on subjects' pelvis and lower extremities at 100 Hz while subjects walked on a dual-belt instrumented treadmill (Bertec, Columbus, OH, USA) collecting ground reaction force data at 1000 Hz. Specifically, 29 anatomical and tracking markers were used during walking and medial knee and ankle markers were added during a standing trial.

2.3. Protocol and biofeedback

After acclimating to treadmill walking at their preferred speed for 5 min, older and young subjects continued walking for 1-min while we collected motion capture and force data. For older subjects, a custom Matlab (Mathworks, Natick, MA) script running a surrogate inverse dynamic model of the ankle (described in more detail previously [7]) estimated the real-time average preferred bilateral ankle power (P_A^{RT}). Briefly, we used 3 markers on each lower leg (fifth metatarsal, lateral malleolus, and shank) and the center of pressure and ground reaction force vector extracted from the treadmill to estimate right and left net ankle moment and angular velocity from step to step. The product of these outcomes estimated stance phase ankle power, from which we extracted P_A^{RT}. We then explained to subjects the timing of push-off and ankle power output, demonstrated rapid and slow ankle angular velocities using heel raises, and demonstrated how ankle moment increases as body weight is shifted forward along the foot.

Subjects completed a 3-min exploration while viewing their step-by-step P_A^{RT} as a dot projected on a screen in front of the treadmill. During this period, subjects practiced increasing and decreasing P_A. Subjects then completed four 1-min trials, in randomized order, while receiving visual biofeedback of their instantaneous P_A^{RT} and targets representing ± 10% and ± 20% of normal (Fig. 1). Target values were selected based on the cumulative literature showing that older adults generate, on average, 20% less peak ankle power than young adults

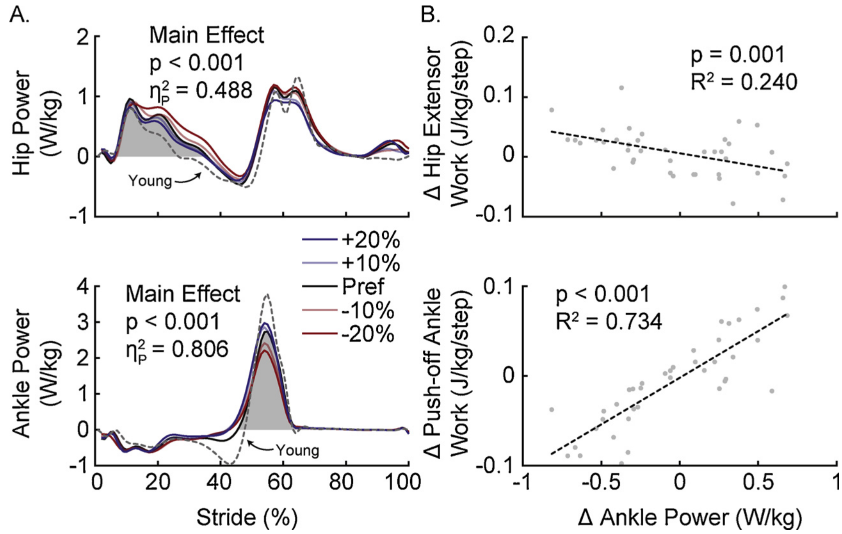

Fig. 2. A) Group mean (n = 10) hip and ankle joint powers plotted against % stride during normal walking (black lines) and when modulating peak ankle power in response to P_A biofeedback. Shaded areas represent positive work used for linear regressions. Main Effect p-value and η_P^2 displayed for reference. Light and dark blue lines correspond to 10% and 20% target increases in ankle power, respectively. Light and dark red lines correspond to 10% and 20% target decreases in ankle power, respectively. Dashed grey lines represent reference data from young adults walking normally. B) Linear regression comparing individual subject changes in peak ankle power (P_A) and changes in hip or ankle positive extensor work. Grey dots represent individual subject average change in positive work, calculated as the positive area under the joint power curve during joint extension, compared to individual subject average change in P_A for each biofeedback trial relative to values from preferred.

walking at the same speed [8,9]. Targets were provided as horizontal lines, and the ordinate range was centered on subjects habitual P_A^{RT} and normalized to evenly distribute target values with a ceiling and floor of ± 30%. Subjects' instantaneous P_A^{RT} updated after every step, using a 4-stride bilateral moving average.

Finally, we again measured PWS and FWS, using the same protocol, to investigate recall effects on gait performance. Specifically, older adults walked overground at their preferred and fastest speed following new instructions to do so "as they had when targeting increases in ankle power on the treadmill".

2.4. Data analysis

We filtered marker trajectories and GRFs using 4th order low-pass Butterworth filters with cutoff frequencies of 6 Hz and 100 Hz, respectively. A static calibration scaled a seven segment, 18 degree-of-freedom models of the pelvis and right and left legs [10] using a leg circumduction task to estimate functional hip joint centers [11]. We estimated bilateral sagittal plane hip, knee, and ankle joint angles, moments, and powers using an inverse dynamics routine described in more detail previously [12]. Briefly, a SIMM Pipeline (Musculographics Inc., Motion Analysis Corp, Santa Rosa, CA) implementing SD/FAST (Parametric Technology Corporation, Waltham, MA) was used to perform a global optimization inverse kinematic routine which computed joint angles at each time point [13]. The routine then calculated net moments and powers via inverse dynamics based on model kinematics, anthropometrics [14], and GRFs.

We analyzed the 20 consecutive strides where subjects most accurately modulated P_A^{RT} to prescribed target values. We extracted the following outcomes: P_A^{RT}, P_A (i.e. extracted from full inverse dynamics), peak hip extensor power generation (H1), peak hip flexor power generation (H3) [15], positive ankle and hip joint work during ankle plantarflexion and hip extension, respectively, and peak hip and ankle joint extension. Joint power and work were normalized to body mass and reported in W/kg and *J*/kg/step, respectively. In order to evaluate the mechanisms by which subjects augmented ankle power, we also extracted peak ankle moment and angular velocity. Given the role of ankle joint kinetics in regulating limb-level push-off performance [16,17], we also calculated peak propulsive force and propulsive impulse from the anterior component of the ground reaction force, normalized to body weight and reported as a percent.

2.5. Statistical analysis

Shapiro-Wilks tests confirmed normal distribution for all outcomes. Independent-samples t-tests first assessed age-related differences in each primary outcome measure ($p < 0.05$) during normal walking, for which we include Cohen's *d* effect sizes. A one-way repeated measures analyses of variance (rmANOVA) tested for main effects of P_A biofeedback in older adults on each of the dependent variables described above, for which we include partial eta squared (η_P^2) effect sizes and F-statistics. When a significant main effect was found, we focused post-hoc pairwise comparisons between values when walking with biofeedback and reference values from preferred walking. We also calculated Pearson's correlation coefficients between changes in P_A and changes in those outcomes having significant main effects.

3. Results

Older adults preferred similar speeds to young adults (old vs young: 1.28 ± 0.20 vs. 1.30 ± 0.12 m/s, p = 0.807, *d* = 0.12), but with 14% smaller peak propulsive forces (p = 0.038, *d* = 1.05), 13% smaller peak ankle moment (p = 0.007, *d* = 1.38), 23% smaller P_A (p = 0.009, *d* = 1.36), 22% less positive ankle push-off work (p = 0.007, *d* = 1.41), and 47% more hip extensor work (p = 0.007, *d* = 1.42). Our real-time estimate of ankle power (P_A^{RT}) elicited systematic changes in ankle power estimated using inverse dynamics (P_A; Fig. 1). We observed a significant multivariate effect of ankle power biofeedback in our overall rmANOVA ($F_{48,112} = 1.980$, p = 0.002, $\eta_P^2 = 0.459$). Older adults increased and decreased P_A by 14% and 17% when targeting ± 20% different from preferred, respectively (main effect: $F_{4,36} = 51.87$, p = 0.006, $\eta_P^2 = 0.852$, pairwise: p-values ≤ 0.002; Fig. 1).

Older adults decreased and increased positive ankle work during push-off by as much as 22% and 15% when targeting -20% and +20% different from their preferred P_A, respectively (main effect: $F_{4,36} = 24.69$, $p < 0.001$, $\eta_P^2 = 0.806$, pairwise: p-values < 0.021; Fig. 2A). We found a strong positive correlation ($p < 0.001$, $R^2 = 0.734$) between changes in P_A and changes in positive ankle work

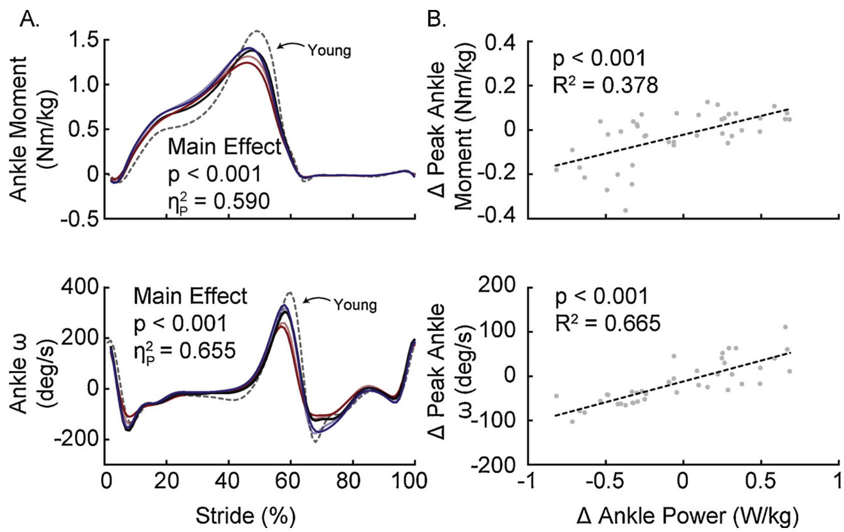

Fig. 3. A) Group mean (n = 10) ankle moment and angular velocity (ω) plotted against % stride during normal walking (black lines) and when modulating peak ankle power in response to P_A biofeedback. Main Effect p-value and η_P^2 displayed for reference. Light and dark blue lines correspond to 10% and 20% target increases in ankle power, respectively. Light and dark red lines correspond to 10% and 20% target decreases in ankle power, respectively. Dashed grey lines represent reference data from young adults walking normally. B) Linear regression comparing individual subject changes in peak ankle power (P_A) and changes in peak ankle moment and angular velocity. Grey dots represent individual subject average change in peak ankle moment and angular velocity, compared to individual subject average change in P_A for each biofeedback trial relative to values from preferred.

during push-off (Fig. 2B). Modulating P_A also augmented H1 ($F_{4,36} = 3.83$, p = 0.011, $\eta_P^2 = 0.298$) and positive hip extensor work ($F_{4,36} = 8.59$, $p < 0.001$, $\eta_P^2 = 0.488$ (Fig. 2A) though we observed no difference in H3 nor positive hip flexor work during late stance. Here, we also found a significant negative correlation (p = 0.001, $R^2 = 0.240$) between P_A and contralateral hip extensor work.

We observed significant main effects of P_A biofeedback on ankle moment ($F_{4,36} = 12.97$, $p < 0.001$, $\eta_P^2 = 0.590$) and angular velocity ($F_{4,36} = 17.12$, $p < 0.001$, $\eta_P^2 = 0.655$). Older adults decreased and increased peak ankle moment by 9% and 3% when targeting -20% and +20% different from preferred P_A, respectively (p-values < 0.014; Fig. 3A). Similarly, older adults decreased peak ankle angular velocity by 17% when targeting -20% different from their preferred P_A ($p < 0.001$) and tended to increase peak ankle angular velocity by 8% when targeting +20% different from preferred P_A (p = 0.058). Accordingly, P_A positively correlated with ankle moment ($p < 0.001$, $R^2 = 0.378$) and, more strongly, with angular velocity ($p < 0.001$, $R^2 = 0.665$).

Older adults adjusted stride length ($F_{4,36} = 3.41$, p = 0.018, $\eta_P^2 = 0.275$) and peak hip extension ($F_{4,36} = 3.76$, p = 0.012, $\eta_P^2 = 0.294$) in response to changes in P_A, though without significant pairwise differences compared to preferred values. A significant main effect of biofeedback on peak ankle plantarflexion ($F_{4,36} = 24.44$, $p < 0.001$, $\eta_P^2 = 0.731$) revealed that values changed by ≥32% when targeting ± 20% different from preferred P_A (p-values ≤ 0.006; Fig. 5).

At the limb level, changes in P_A were mirrored by changes in peak propulsive force ($F_{4,36} = 18.55$, $p < 0.001$, $\eta_P^2 = 0.673$) and propulsive impulse ($F_{4,36} = 8.71$, $p < 0.001$, $\eta_P^2 = 0.492$; Fig. 4A). The ANOVA was supported by significant positive correlations between P_A and both peak propulsive force ($p < 0.001$, $R^2 = 0.395$) and propulsive impulse (p = 0.005, $R^2 = 0.188$) across conditions.

Finally, recalling increased P_A following biofeedback yielded faster preferred (PWS) but not fast (FWS) overground walking speed (p = 0.010, *d* = 0.54) (Table 1).

4. Discussion

Despite hallmark deficits in ankle power output and a redistribution to hip power output, our older adult subjects were capable of modulating P_A when appropriately encouraged via visual biofeedback in a manner consistent with our hypothesis. Moreover, power generation at the ankle and hip were inexorably linked in older adults; as hypothesized, walking with larger than preferred P_A decreased hip power output and reversed the distal-to-proximal redistribution while walking with smaller than preferred P_A increased hip power output and exacerbated that redistribution. Also as hypothesized, recall of increased P_A yielded faster preferred walking speeds. Finally, data suggest that older adults modulated ankle power more by changing ankle angular velocity than by changing ankle moment. Together, our results allude to the potential for promising translational efforts; reversing the distal-to-proximal redistribution may improve walking economy, faster walking speeds may improve community independence, and mechanistic outcomes encourage the development of push-off training interventions outside the lab.

This study provides the first evidence that older adults can volitionally modulate ankle power at their preferred walking speed, building confidence that they retain the capacity for more youthful patterns of joint-power generation. Older adults frequently suffer from muscle weakness due to sarcopenia [18–20] and impaired neural control of distal leg muscles [21,22]. These physiological changes might suggest that older adults are prohibited from walking with greater P_A [23]. In contrast, our older adults increased P_A by as much as 14% and attenuated their deficits to group-average values from young adults. Nevertheless, that age-related deficit persisted, which has at least two possible explanations. Our older adult subjects may have reached their maximum capacity to generate P_A (i.e., +14% on average) when targeting 20% greater than normal values. Alternatively, our older subjects may have simply opted not to further increase P_A beyond the measured values. We note that young subjects, in the absence of sarcopenia or altered neural control, previously increased P_A by only 13%, on average, when targeting 20% greater than normal values [24]. We would thus caution against assuming that our older subjects were prohibited from generating larger values and encourage the inclusion of more challenging targets in future studies. Indeed, older adults walking at their preferred speed may increase P_A by up to 50% [25]. It is also likely that older subjects could better accommodate biofeedback through training. Nevertheless, there may be age-related functional limitations at play. As we discuss more below, that older adults appear to rely more on ankle angular velocity than ankle moment to modulate ankle power implies that age-related changes in rate of force generation

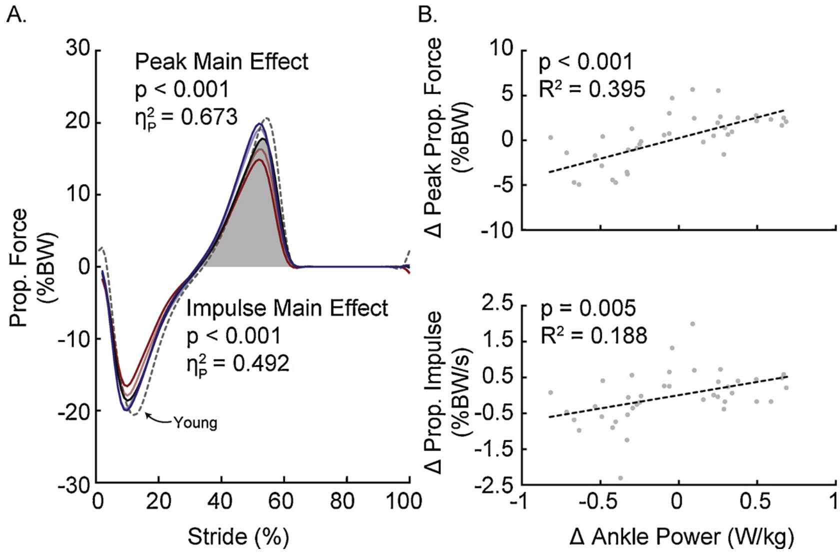

Fig. 4. A) Group mean (n = 10) propulsive ground reaction force plotted against % stride during normal walking and when modulating peak ankle power in response to P_A biofeedback. Shaded areas represent propulsive impulse used in linear regression. Main Effect p-value and η_P^2 displayed for reference. Light and dark blue lines correspond to 10% and 20% target increases in ankle power, respectively. Light and dark red lines correspond to 10% and 20% target decreases in ankle power, respectively. Dashed grey lines represent reference data from young adults walking normally. B) Linear regression comparing individual subject changes in peak ankle power (P_A) and changes in peak propulsive force and propulsive impulse. Grey dots represent individual subject average change in peak propulsive force and propulsive impulse, calculated as the positive area under the anterior GRF curve during stance, compared to individual subject average change in P_A for each biofeedback trial relative to values from preferred.

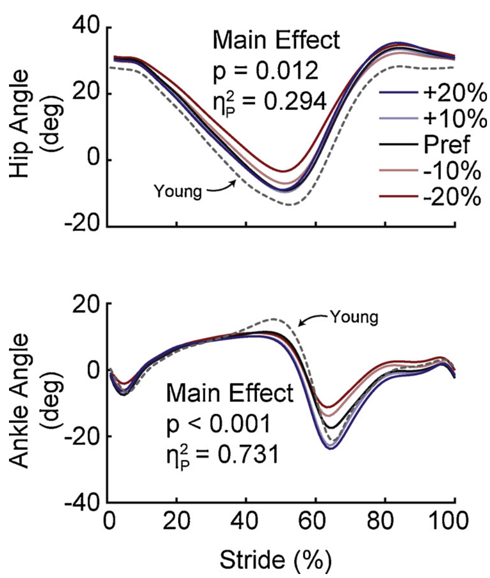

Fig. 5. Group mean (n = 10) hip and ankle angle plotted against % stride during normal walking and when modulating peak ankle power in response to P_A biofeedback. Light and dark blue lines correspond to 10% and 20% target increases in ankle power, respectively. Light and dark red lines correspond to 10% and 20% target decreases in ankle power, respectively. Dashed grey lines represent reference data from young adults walking normally. Main Effect p-value and η_P^2 displayed for reference.

Table 1
Overground walking speeds before and after biofeedback.

	Older Adults		Young Adults
	PWS (m/s)	FWS (m/s)	PWS (m/s)
Baseline	1.31 ± 0.20	1.79 ± 0.20	1.30 ± 0.12
Post	1.45 ± 0.29	1.76 ± 0.24	–
p-value	< 0.010	0.283	–
Difference	10.80%	–	–

PWS: preferred walking speed. FWS: fast walking speed.

and recruitment of Type II muscle fibers may be relevant [26].

As a major goal of this study, we accept our hypothesis that modulating ankle power during push-off directly impacts the distal-to-proximal redistribution. While our reported correlation between changes in ankle power and hip extensor work ($R^2 = 0.240$) may be interpreted as modest to moderate [27], tradeoffs between ankle and hip power output are perhaps not surprising given that decreases in ankle power output in old age are so often accompanied by increased hip power output [3,28–31]. In young adults, Lewis and Ferris (2008) asked young subjects to push-off more, who did so with increased ankle angular momentum and decreased hip joint moments, though without changing P_A [32]. More recently, using biofeedback to increase F_P in older subjects elicited reduced ipsilateral hip flexor power output despite no change in P_A [3]. In contrast, using targeted biofeedback, older subjects in this study simultaneously walked with more P_A and less contralateral hip extensor power generation - the clearest evidence yet that the distal-to-proximal redistribution may be reversible. Together, our results highlight that the specific response to biofeedback rests on knowing the appropriate biomechanical outcome to target.

Older adults modulated P_A more via ankle angular velocity than via peak ankle moment. We were particularly interested in understanding the contributions of ankle moment and angular velocity to changes in P_A as a conduit to translate our infrastructure to the community. Ankle power is the product of ankle moment and angular velocity. Indeed, both ankle moment and ankle angular velocity positively correlated with changes in P_A. However, ankle moment demonstrated relatively modest changes compared to angular velocity, which was more strongly correlated with changes in P_A. In another study, older adults responded to impeding forces that increased the propulsive demands of walking to their maximum with 50% more P_A without changing peak ankle moment [25]. Those authors suggested that ankle moment may be a functionally limiting impairment in elderly gait [23]. Accordingly, regulating plantarflexor muscle activity in response to biofeedback may augment ankle angular velocity better than ankle moment. Thus, accelerometers or inertial measurement units may serve as surrogates for

P_A, empowering the personalized prescription of push-off training interventions outside the lab.

Our final hypothesis was that older adults would increase their preferred but not fast walking speed when asked to recall increased P_A in a transfer to overground walking. Strength gains from power training interventions are more likely to improve fast than preferred walking speeds [33]. One explanation is that improved muscular capacities do not alter the instinctive utilization of those capacities nor habitual locomotor patterns. Conversely, our older adult subjects did not increase their fastest walking speed but did increase their preferred walking speed by 11% when asked to walk overground as they had when targeting increased P_A on the treadmill. Our study provided no immediate benefit to muscular capacity per se. Instead, P_A biofeedback encouraged different patterns of mechanical power generation, the recall of which transferred to faster overground walking. We suggest that a similar biofeedback paradigm could complement more conventional strength training for a patient specific approach to restoring push-off performance - strength training to restore muscular capacities when needed and biofeedback to encourage new volitional control strategies that leverage those capacities.

Older adults appear to have improved their preferred walking speed via increases in propulsive forces exerted during push-off that accompanied greater P_A. Previously, biofeedback designed to increase propulsive forces had no effect on P_A [3]. This suggests that while increasing ankle power is not a prerequisite for increasing propulsive forces, increasing ankle power does increase propulsive forces. Hsiao et al. demonstrated that propulsive forces are important determinants of walking speed [34,35]. Thus, although we collected no overground biomechanical data, we suspect that recall of increased P_A, with concomitant increases in peak propulsive forces, underlies subjects' faster preferred walking speeds. Further, these results are the first to suggest that biofeedback during treadmill walking at a constant speed may transfer well to self-selected overground walking behavior.

Subjects were healthy and physically active and may not represent those considered at risk for mobility impairment. Nevertheless, these older adults walked with many of the hallmark biomechanical changes attributed to elderly gait. Although we found strong agreement with inverse dynamic estimates of ankle power, we neglected inertial effects and used a simplified ankle joint center in our real-time surrogate model. We analyzed the 20 consecutive strides during which subjects demonstrated the best accuracy for any given target. It is possible that subjects had not grown fully accustomed to each target. Indeed, motor learning of novel movement strategies during adaptation to biofeedback remains an important future direction.

5. Conclusion

Older adults are capable of increasing P_A through targeted ankle power biofeedback based on real-time inverse dynamics – effects that are accompanied by diminished hip power output and attenuation of the distal-to-proximal redistribution. The associated increase in PWS during recall suggests a functional benefit to increased ankle power output via transfer to overground walking. Finally, our mechanistic insights allude to translational success using ankle angular velocity as a surrogate to modulate P_A through biofeedback, an obvious clinical application of wearable sensor technologies.

Conflict of interest

The authors report no conflict of interest.

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