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Increasing thigh extension with haptic feedback affects leg coordination in young and older adult walkers

Mohsen Alizadeh Noghani [a], Ehsan Sharafian M. [b], Ben Sidaway [c], Babak Hejrati [b],*

[a] Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, 46556, IN, United States of America
[b] Biorobotics and Biomechanics Lab, Department of Mechanical Engineering, University of Maine, Orono, 04469, ME, United States of America
[c] School of Physical Therapy, Husson University, Bangor, 04401, ME, United States of America

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ABSTRACT

Interlimb coordination can be used as a metric to study the response of the neuromuscular system to mechanical perturbations and behavioral information. Behavioral information providing haptic feedback on thigh angle has been shown to increase stride length and consequently walking speed, but the effect of such feedback on limb coordination has not been determined. The current work investigates the effects of this feedback on lower-limb coordination and examines if such effects are dependent on the age of the walker. Existing kinematic data were examined from 10 young and 10 older adults during overground walking at self-selected normal and fast speeds and with thigh extension haptic feedback. Using sagittal angles of the lower-limb segments, we quantified changes in the mean of continuous relative phase ($ACRP$) and its standard deviation ($VCRP$) for thigh-shank and shank-foot segment pairs, over windows of 10% of gait cycle around peak thigh extension, toe-off, and heel strike. We found that the haptic feedback resulted in more in-phase movement (i.e., decreased $ACRP$, Cohen's d: 0.56-1.46), and larger coordination variability (i.e., increased $VCRP$, Cohen's d: 0.60-1.50) of the segment pairs across the three windows. Additionally, the young adults exhibited lower $ACRP$ than older adults (Cohen's d=1.02) and higher $VCRP$ (Cohen's d=1.02) when the feedback was provided. The results suggest that the haptic feedback elicited distinct adaptations in the neuromuscular system and that this response differed between young and older adults.

1. Introduction

The smooth coordination of the limbs seen in the gait of healthy individuals is the achievement of a complex neuromuscular system. The ability of the neuromuscular system to produce an efficient gait pattern can be challenged by neural disorders such as Parkinson's disease (Roemmich et al., 2013) and cerebral palsy (Kuntze et al., 2021), by age-related changes (Hafer and Boyer, 2018), and even by the requirement for the system to engage in attention-demanding tasks while walking (Ghanavati et al., 2014; Wang et al., 2021a). To analyze the effect of such neuromuscular perturbations on gait, continuous relative phase (CRP) can be used to quantify interlimb coordination. CRP computes the phase of a pair of segments or joint angles relative to each other (Lamb and Stöckl, 2014). Previous work has used CRP to understand how external (e.g., walking terrain) or internal (e.g., muscle fatigue) constraints and perturbations impact limb coordination. For example, while carrying loads, thigh-shank and shank-foot coordination variability change as a function of load size and biological sex (Hoolihan et al., 2023). Regularity and slope of the walking surface affect knee-hip coordination (Ippersiel et al., 2022), and deviations from typical lower-limb coordination patterns have been observed in patients with knee osteoarthritis (Wang et al., 2021c). It has been found that using passive exoskeletons can compromise thorax-pelvis coordination during lifting tasks (Madinei et al., 2021). Other studies have investigated changes in coordination due to surface inclination (Dewolf et al., 2020), turning curvature (Huang et al., 2020), muscle fatigue during sit-to-stand Chen and Chou (2022), and running at maximal sprinting speed (Whitacre et al., 2024).

The pattern of coordination seen in gait can also be altered by the provision of feedback to the performer. In particular, tactile stimuli have been found to be an effective mode of feedback to adjust gait coordination. Previous studies have provided rhythmic feedback on the arms (Alizadeh Noghani et al., 2023) or the feet (Zhang et al., 2020) to modulate the cadence of the lower and upper limbs. Haptic feedback on the shank can encourage adjusting ankle moment at push-off (Schenck et al., 2019) and foot progression angle and step width (Chen et al., 2017). Given the importance of gait speed as a metric of independent mobility and wellbeing (Hardy et al., 2007), tactile feedback

* Correspondence to: 256 Ferland EEDC, 75 Long Rd, Orono, Maine, 04469, United States of America.
E-mail address: babak.hejrati@maine.edu (B. Hejrati).

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has also been used to increase the walking speed. Previous studies have modified peak thigh extension as a proxy for stride length in young (Alizadeh Noghani et al., 2021) and older adults (Hossain et al., 2023) to achieve this outcome.

While these studies have described the response to the haptic feedback using segment-specific metrics such as thigh extension or spatiotemporal parameters (e.g., stride length, speed, and cadence), the question of how such feedback impacts the coordination and motion of the limbs relative to each other remains unanswered. Therefore, the purpose of this work is to investigate the changes in coordination patterns of the lower limbs as a result of providing feedback designed to increase thigh extension, and consequently walking speed, in young and older adults. This is the first study to investigate the effect of tactile feedback for gait training on coordination in these two age groups. Motivated by the evidence from the literature suggesting that changes in coordination reflect neuromuscular adaptations and that such adjustments differ between young and older adults, we hypothesized that the feedback encouraging increased thigh extension would (1) induce changes in interlimb coordination and its variability, and (2) elicit different coordination responses in the two age groups.

2. Methods

2.1. Participants

The data from two previous studies with young adults (Alizadeh Noghani et al., 2021) (n = 10, age: 25.9 ± 6.26 years, height: 1.72 ± 0.12 m, mass: 72.4 ± 14.7 kg, sex: 6 M, 4 F) and older adults (Hossain et al., 2023) (n = 10, age: 68.5 ± 4.00 years, height: 1.68 ± 0.08 m, mass: 72.0 ± 9.96 kg, sex: 3 M, 7 F) were analyzed. The participants included healthy young adults and community-dwelling older adults who could walk independently without any assistive devices. Individuals with neurological disorders (e.g., Parkinson's disease, stroke, multiple sclerosis) or diagnosed cognitive impairments were not considered for participation. All the participants provided written consent. The collection of data in the previous studies and their use in this work were approved by the University of Maine's Institutional Review Board (IRB 2019-04-15).

2.2. Haptic feedback experiments

In both studies, a wearable haptic feedback system (Alizadeh Noghani et al., 2021) was used to provide haptic cues to increase the peak thigh extension (θ_{PTE}) during overground walking on a 54 m × 3 m track on level ground (Fig. 1(a)). Haptic cells, each comprised of 3 vibrational motors, were placed on the posterior side of the participants' thighs. During walking, a peak detection algorithm (Alizadeh Noghani et al., 2021) monitored the thigh angle to determine θ_{PTE}; if it was below a target value, a vibration was provided to the participant as a signal for increasing θ_{PTE} in the next gait cycle, which is a commonly used feedback strategy (Shull et al., 2013; Xia et al., 2020). The cue aimed to increase the users' peak thigh extensions compared to the baseline (i.e., during normal walking without feedback) and, thereby, increase their walking speed. The target value of θ_{PTE} for each participant was individualized as a function of their own average θ_{PTE} during walking at a self-selected normal speed (Alizadeh Noghani et al., 2021; Hossain et al., 2023). Before the start of the experiments, the participants were instructed to increase their thigh extension according to the feedback to the best of their ability and as long as their walking felt safe and natural. It should be noted that no instructions about changing walking speed were given to the participants.

The feedback system delay from the occurrence of θ_{PTE} to the start of vibration was measured to be 137 ms on average with a standard deviation of 53 ms (Alizadeh Noghani, 2021; Alizadeh Noghani et al., 2021). Considering that θ_{PTE} occurred near the end of the stance phase (Fig. 1), the users had adequate time after receiving the cue to increase their thigh extension on the next cycle. The segment angles of thigh (θ_T), shank (θ_S), and foot (θ_F) were recorded during the experiments at 60 Hz by inertial measurement units (Xsens Technologies B.V., Enschede, The Netherlands), and heel strike and toe-off events were identified using the sagittal foot angle (Mariani et al., 2013) (Fig. 1(b)). In post-processing, for each gait cycle, we calculated the stride time $ST\,(s)$ using the number of samples between two consecutive heel strikes, and approximated the cadence ($\frac{\text{steps}}{\text{min}}$) as $\frac{120}{ST}$. We computed stride length by double-integration of foot acceleration signal with zero-velocity updates (Hossain et al., 2023), which was normalized by dividing by the participant's height. Then, for each gait cycle, we obtained the normalized speed by dividing its normalized stride length by its stride time.

2.3. Data analysis

The thigh, shank, and foot segments' angles during the feedback trial (FB), walking at self-selected normal speed (N), and walking at self-selected fast speed (F) were analyzed. The sagittal segment angles between consecutive heel strikes were separated and normalized to 0%–100% of the gait cycle (GC) by linearly interpolating at 200 equidistance points, each representing 0.5% progression within the cycle.

The results were subsequently processed to obtain the CRPs (Fig. 2) (Wang et al., 2021c). First, to improve the linearity of the phase estimate, the segment angles were centered around zero (Lamb and Stöckl, 2014),

$$\hat{\theta}(t_i) = \theta(t_i) - \frac{\max(\theta) + \min(\theta)}{2}, \tag{1}$$

where $\theta(t_i)$ and $\hat{\theta}(t_i)$ represent the segment angle and its zero-centered value at each time point, t_i, of a GC. Then, the Hilbert transform of $\hat{\theta}$, denoted by $\xi(t)$, which is a complex and analytical signal, was computed,

$$\xi(t) = \hat{\theta}(t) + iH(t). \tag{2}$$

The phase angle of the segment at each t_i, $\phi(t_i)$, was obtained using the real ($\hat{\theta}(t_i)$) and imaginary ($H(t_i)$) parts of $\xi(t_i)$ and the four-quadrant inverse tangent function, $atan2$, in MATLAB (MathWorks, Natick, MA, USA),

$$\phi(t_i) = atan2(H(t_i), \hat{\theta}(t_i)). \tag{3}$$

To eliminate the discontinuity that occurs using $atan2$ at 180°, ϕ was translated to the $[0°, 360°]$ range. Then, the CRP (ϕ_{pd}), with a range of $[-180°, 180°]$, was calculated between two segments by considering one as proximal and the other as distal,

$$\phi_{pd}(t_i) = \phi_p(t_i) - \phi_d(t_i), \tag{4}$$

where ϕ_p represents the proximal segment's phase angle and ϕ_d represents the distal segment's phase angle. Using Eq. (4), ϕ_{pd} was computed for thigh-shank (thigh: proximal, shank: distal) and shank-foot (shank: proximal, foot: distal) segment pairs.

A CRP of 0° corresponds to in-phase coupling and the negative and positive CRPs denote whether the proximal segment is lagging or leading relative to the distal segment, respectively. For each participant, the CRPs were calculated for 15 cycles at the end of the trial but at least 5 cycles before the participant stopped walking to capture the cycles during the participant's steady-state walking. The ensemble mean ($ACRP$) and standard deviation ($VCRP$) of the resulting CRP trajectories were computed at each time point t_i of a GC. The $VCRP$ for each participant shows the cycle-to-cycle variations across the entire gait cycle and was used to represent coordination variability in our analysis.

To perform hypothesis testing on whether there were differences in $ACRP$ and $VCRP$ among the three trials and the two groups of young and older adults, we compared them in windows of ±5% GC centered around peak thigh extension (PTE), toe-off (TO), and heel strike (HS).

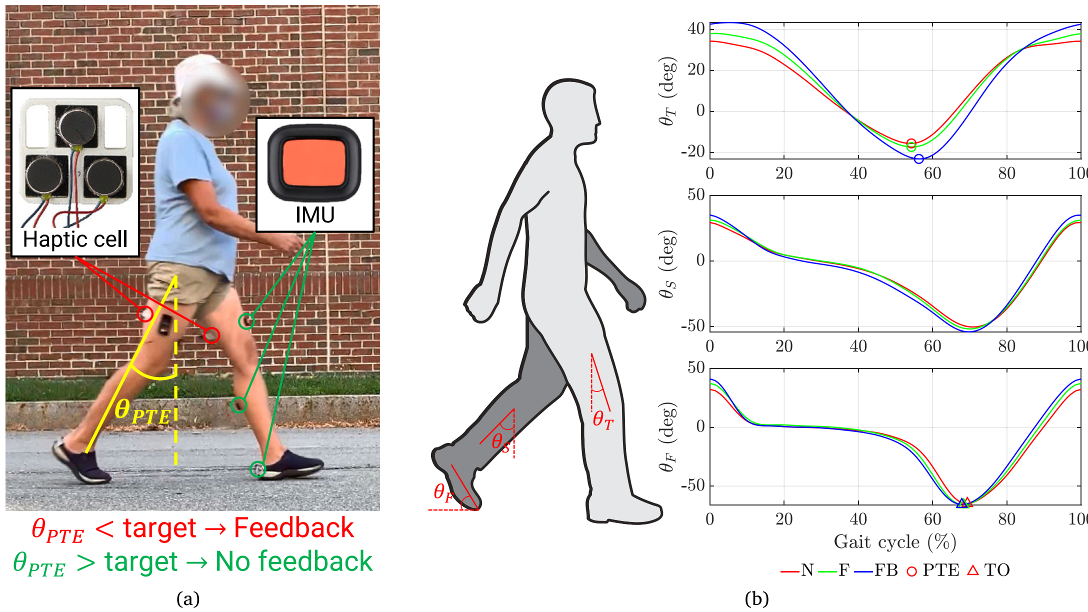

Fig. 1. (a) The feedback system, the peak thigh extension (θ_{PTE}), and the rule for providing feedback. (b) The definition of segment angles of thigh (θ_T), shank (θ_S), and foot (θ_F) and the mean of the segment angles of all 20 participants. The gait cycle starts and ends with heel strikes, and ∘ and ▵ indicate peak thigh extension (PTE) and toe-off (TO), respectively.

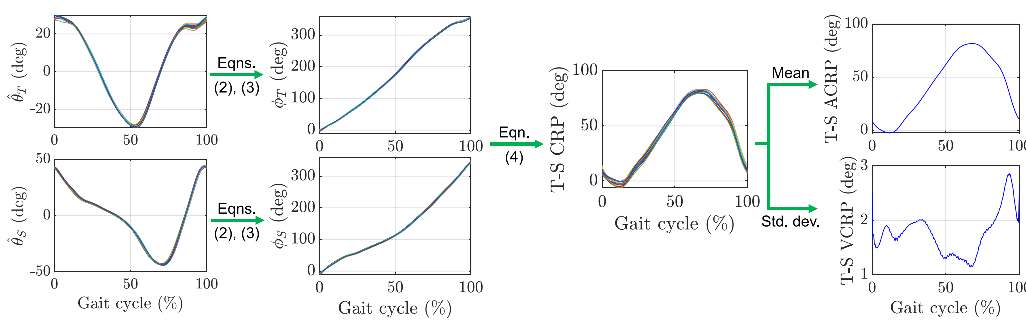

Fig. 2. The process to compute $ACRP$ and $VCRP$ for 15 cycles of the normal walking trial of a single subject. $\hat{\theta}_T$ and $\hat{\theta}_S$ refer to the trajectories centered around 0, from which phase angles ϕ_T and ϕ_S are obtained. The thigh-shank CRP (denoted by T-S CRP) is calculated according to Eq. (4) by considering the thigh as the proximal segment and the shank as the distal segment. It is then used to compute T-S $ACRP$ by taking the mean, and T-S $VCRP$ by taking the standard deviation.

The PTE window was selected because the feedback aimed to increase θ_{PTE}. The window around TO allowed us to characterize the changes at the end of the stance phase, and by considering HS, we investigated how responding to the feedback altered coordination patterns at the end of one gait cycle and initiation of the next. The size of the windows (10% of GC) was selected to cover each event while avoiding significant overlaps between PTE and TO (Fig. 1), and also account for the uncertainties in identifying TO and HS from the sagittal foot angle.

For visualization (Fig. 3), the results of $ACRP$ and $VCRP$ were averaged across the participants in each group of young and older adults to obtain the mean $ACRP$ (denoted by $MACRP$) and the mean $VCRP$ (denoted by $MVCRP$),

$$MACRP(t_j) = \frac{1}{n}\sum_{i=1}^{n} ACRP_i(t_j), \tag{5}$$

$$MVCRP(t_j) = \frac{1}{n}\sum_{i=1}^{n} VCRP_i(t_j), \tag{6}$$

where $n = 10$ is the number of participants in each group, i counts the participants, and j represents progression in the gait cycle (Wang et al., 2021c).

2.4. Statistical analysis

We performed repeated measures analysis of variance (ANOVA) on the data of the 10 young adults and 10 older adults using SPSS v29 (IBM Corporation, Armonk, NY, USA). We excluded sex as a factor in our statistical analysis based on several considerations of (1) an exploratory analysis that did not identify sex or its interaction with walking speed as a significant effect for the immediate response to the feedback (represented by θ_{PTE} and normalized stride length) (all p-values > 0.187), (2) the relatively small sample sizes of males and females within each age group, and (3) prior research reporting no sex differences in $VCRP$ during walking (Hoolihan et al., 2023). In the final model, θ_{PTE}, the spatiotemporal parameters, $ACRP$, and $VCRP$ were the dependent variables; the walking condition with 3 levels of N, F, and FB was considered as the within-subjects factor, and the age group with 2 levels of young and old was the between-subjects factor. The interaction of walking condition and age was also included in the model. The sphericity assumption was tested with Mauchly's test and Greenhouse–Geisser correction was applied if rejected. When the main or interaction effects were significant, post-hoc pairwise comparisons were performed with the p-values adjusted using the Bonferroni method

Table 1
The peak thigh extension (θ_{PTE}) and spatiotemporal parameters' means (standard deviations) and ANOVA results for walking condition (WC), age group (Age), and their interaction (WC × Age); significant differences between N and other conditions are indicated by ∗, while for the $F-FB$ pair significance is shown by †. ANOVA effect sizes are reported by partial eta-squared (η_p^2). The p-values and effect sizes for the significant pairwise comparisons are presented in the Appendix (Table A.4).

Parameter	WC			p	η_p^2	Age		p	η_p^2	WC × Age	
	N	F	FB			Young	Old			p	η_p^2
θ_{PTE} (deg)	16.24 (3.85)	18.53 (4.04)*	24.78 (6.30)$^{\dagger *}$	**<0.001**	0.77	21.46 (7.31)	18.23 (3.81)	0.065	0.17	**<0.001**	0.49
Stride length ($\frac{m}{m}$) (height-normalized)	0.86 (0.09)	0.95 (0.11)*	1.09 (0.17)$^{\dagger *}$	**<0.001**	0.83	1.01 (0.17)	0.93 (0.14)	0.096	0.14	**<0.001**	0.49
Speed ($\frac{m/s^2}{m}$) (height-normalized)	0.80 (0.11)	0.98 (0.14)*	0.95 (0.16)*	**<0.001**	0.66	0.91 (0.11)	0.90 (0.20)	0.863	0.02	0.368	0.05
Cadence ($\frac{steps}{min}$)	111.08 (8.94)	123.23 (10.27)*	104.40 (15.13)$^{\dagger *}$	**<0.001**	0.67	109.69 (13.39)	116.12 (14.02)	0.141	0.11	**0.005**	0.30

to control for the familywise Type I error rate. All the statistical determinations were made at a 5% significance level (i.e., $\alpha = 0.05$), and partial eta-squared (η_p^2) and Cohen's d were used to quantify effect sizes. Specifically, Cohen's d for paired samples was calculated for contrasts between two walking conditions and walking conditions within each age group, while the independent-samples d was used as the effect size for contrasts between age groups and between walking conditions of different age groups. The thresholds for small, medium, and large effect sizes were 0.01, 0.06, 0.14 for η_p^2 and 0.2, 0.5, and 0.8 for the absolute value of d (Cohen, 1988). When the sign of d is specified, a negative value indicates the first condition of the pair had a smaller mean, while a positive value signifies that the first condition of the pair had a larger mean.

3. Results

3.1. Spatiotemporal parameters

Post-hoc analysis showed significant differences in the peak thigh extension (θ_{PTE}) between all paired comparisons ($N-FB$, $F-FB$, and $N-F$), with the greatest θ_{PTE} occurring in the FB condition (Table 1). The interaction effect was significant, revealing that the young participants had greater θ_{PTE} during the FB condition than the older adults ($p < 0.001$, $d = 1.92$).

Post-hoc analysis identified significant differences in stride length for all between-conditions comparisons, with the greatest stride length being observed in the FB condition. The young participants achieved greater stride lengths than the older group during the FB condition ($p = 0.004$, $d = 1.46$). The pairwise post-hoc analysis of the speed identified differences between $N-F$ ($p < 0.001$, $d = -2.33$) and $N-FB$ ($p < 0.001$, $d = -1.26$).

There were significant differences in cadence for all pairwise comparisons ($p < 0.019$, d: 0.52-1.70), with the greatest cadence exhibited during the F condition. The older participants demonstrated greater cadence than the young walkers during the FB condition ($p = 0.012$, $d = 1.24$).

3.2. Interlimb coordination ($ACRP$)

In the peak thigh extension window (PTE), the walking condition was a significant main effect for both the thigh-shank and shank-foot $ACRP$s, while age was a significant effect only for the former (Table 2 and Fig. 3). Post-hoc analysis revealed that, for the thigh-shank $ACRP$, there were significant differences between the $N-FB$ ($p < 0.001$, $d = 0.56$) and $F-FB$ ($p = 0.006$, $d = 0.79$) comparisons. Post-hoc analysis of the shank-foot $ACRP$ indicated differences in the $N-FB$ ($p = 0.003$, $d = 0.79$) and $N-F$ ($p < 0.001$, $d = 1.07$) pairs. The interaction term was significant for the shank-foot $ACRP$, and post-hoc tests suggested that the young participants had smaller $ACRP$s during the FB condition than the older adults ($p = 0.035$, $d = 1.02$). Significant differences were also observed between $N-F$ of both the young ($p = 0.031$, $d = 0.78$) and older adults ($p = 0.004$, $d = 1.49$), and between $N-FB$ of the young adults ($p = 0.002$, $d = 1.20$).

In the toe-off window (TO), the walking condition and age were significant main effects only for the thigh-shank $ACRP$. Pairwise comparisons revealed significant differences in the thigh-shank $ACRP$s between all pairs of walking conditions ($p < 0.030$, d: 0.65–1.46).

In the heel strike window (HS), a significant main effect of walking condition was identified only for the thigh-shank $ACRP$, whereas age was a significant effect for both the thigh-shank and shank-foot $ACRP$s. Post-hoc analysis showed differences in the thigh-shank $ACRP$ of $N-FB$ ($p < 0.001$, $d = 1.33$) and $F-FB$ ($p = 0.021$, $d = 0.70$) pairs.

3.3. Interlimb coordination variability ($VCRP$)

In the PTE window, the walking condition had a significant effect on the thigh-shank $VCRP$. Post-hoc tests revealed significant differences in the $N-FB$ ($p = 0.027$, $d = -0.64$) and $F-FB$ ($p = 0.013$, $d = -0.67$) pairs (Table 3).

In the TO window, the walking condition was a significant predictor for the $VCRPs$ of thigh-shank and shank-foot pairs. Post-hoc analysis identified differences in the $N-FB$ pair for thigh-shank ($p = 0.004$, $d = -0.81$) and shank-foot ($p < 0.001$, $d = -0.91$). Meanwhile, for $F-FB$, a significant difference was detected only for thigh-shank ($p = 0.020$, $d = -0.60$). The interaction of walking condition and age was significant for both the thigh-shank and shank-foot pairs. Subsequent tests identified differences in the thigh-shank $VCRP$ only in the young participants, namely in $N-FB$ ($p = 0.003$, $d = -1.02$) and $F-FB$ ($p = 0.002$, $d = -1.14$). For the significant interaction term of the shank-foot $VCRP$, there was a difference between the young and old groups during FB ($p = 0.035$, $d = 1.02$), and for the young participants between $N-FB$ ($p < 0.001$, $d = -1.50$) and $F-FB$ ($p = 0.005$, $d = -1.43$) pairs.

In the HS window, the walking condition was significant only for thigh-shank $VCRP$, with post-hoc analysis showing differences between the N and FB conditions ($p = 0.003$, $d = -0.78$). While the interaction effect was significant, the corresponding post-hoc tests did not identify a significant difference between the young and older adults in any of the three walking conditions. However, in the young participants, there were differences in the $N-FB$ ($p = 0.005$, $d = -1.49$) and $F-FB$ ($p = 0.02$, $d = -1.05$) contrasts.

4. Discussion

The primary purpose of this study was to examine how the provision of haptic feedback to the thighs alters the sagittal plane coordination of the legs during gait. Our hypotheses were that (1) the feedback would change the patterns of coordination and the variability of those patterns, and (2) the changes in coordination of young and older adults would be quantitatively different. The presence of such feedback increased peak thigh extension (θ_{PTE}), which resulted in increased stride length, and, consequently, walking speed reached levels close to that seen in fast walking, despite the lower cadence. In addition,

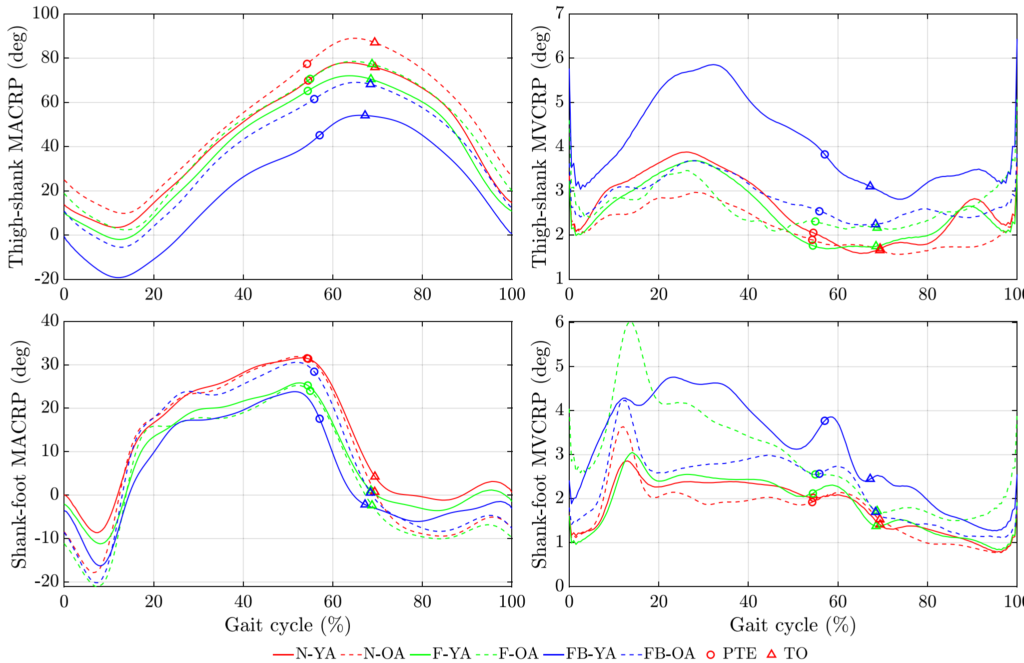

Fig. 3. The thigh-shank and shank-foot $MACRP$ (the left column) and $MVCRP$ (the right column) trajectories through the gait cycle for young adult (YA, solid lines) and older adult (OA, dashed lines) participants during Normal (N, red), Fast (F, green), and Feedback (FB, blue) conditions. The gait cycle starts and ends with heel strikes, and ∘ and △ indicate peak thigh extension (PTE) and toe-off (TO), respectively.

Table 2
The $ACRP$ values (representing coordination), in degrees, in the PTE, TO, and HS windows, reported as means (standard deviations) for the thigh-shank (T-S) and shank-foot (S-F) pairs; significant differences between N and other conditions are indicted by $*$, while for the $F-FB$ pair significance is shown by †. ANOVA effect sizes are reported by partial eta-squared (η_p^2). The p-values and effect sizes for the significant pairwise comparisons are presented in the Appendix (Table A.5).

Window	WC			p	η_p^2	Age		p	η_p^2	WC × Age	
	N	F	FB			Young	Old			p	η_p^2
PTE	73.25	67.62	53.64	**<0.001**	0.52	59.94	69.73	**0.016**	0.28	0.242	0.08
(T-S)	(8.56)	(11.45)	(16.60)$^{\dagger *}$			(15.69)	(12.62)				
PTE	30.20	21.99	20.98	**<0.001**	0.35	23.09	25.70	0.483	0.28	**0.025**	0.18
(S-F)	(9.00)	(10.77)*	(10.85)*			(10.13)	(11.63)				
TO	81.11	73.30	59.39	**<0.001**	0.52	65.57	76.96	**0.004**	0.37	0.360	0.06
(T-S)	(10.27)	(11.77)*	(16.63)$^{\dagger *}$			(16.24)	(13.31)				
TO	3.93	0.70	1.12	0.295	0.07	3.33	0.51	0.299	0.06	0.265	0.07
(S-F)	(8.17)	(9.02)	(7.54)			(8.90)	(7.43)				
HS	20.92	15.56	5.99	**<0.001**	0.47	8.62	19.69	**0.012**	0.30	0.840	0.01
(T-S)	(13.02)	(13.18)	(10.67)$^{\dagger *}$			(11.57)	(13.46)				
HS	−4.60	−6.78	−6.81	0.423	0.05	−2.28	−9.84	**<0.001**	0.50	0.468	0.04
(S-F)	(7.26)	(8.44)	(6.11)			(7.26)	(5.07)				

Table 3
The $VCRP$ values (representing coordination variability), in degrees, in the PTE, TO, and HS windows, reported as means (standard deviations) for the thigh-shank (T-S) and shank-foot (S-F); significant differences between N and other conditions are indicted by $*$, while for the $F-FB$ pair significance is shown by †. ANOVA effect sizes are reported by partial eta-squared (η_p^2). The p-values and effect sizes for the significant pairwise comparisons are presented in the Appendix (Table A.6).

Window	WC			p	η_p^2	Age		p	η_p^2	WC × Age	
	N	F	FB			Young	Old			p	η_p^2
PTE	1.98	1.95	3.00	**0.004**	0.31	2.48	2.14	0.394	0.04	0.094	0.13
(T-S)	(0.72)	(0.74)	(1.74)$^{\dagger *}$			(1.55)	(0.85)				
PTE	2.01	2.54	3.00	0.113	0.12	2.51	2.52	0.962	<0.01	0.264	0.07
(S-F)	(0.55)	(2.13)	(1.03)			(1.04)	(1.76)				
TO	1.71	1.96	2.74	**<0.001**	0.35	2.25	2.03	0.519	0.02	**0.025**	0.18
(T-S)	(0.71)	(0.85)	(1.37)$^{\dagger *}$			(1.26)	(0.86)				
TO	1.54	1.69	2.26	**0.001**	0.30	1.89	1.77	0.562	0.02	**0.006**	0.24
(S-F)	(0.40)	(0.73)	(0.91)*			(0.87)	(0.66)				
HS	2.32	2.71	3.16	**0.016**	0.20	2.74	2.72	0.946	<0.01	**0.008**	0.23
(T-S)	(0.66)	(1.23)	(1.26)*			(1.12)	(1.14)				
HS	1.12	1.84	1.68	0.323	0.05	1.38	1.71	0.498	0.03	0.167	0.10
(S-F)	(0.25)	(2.93)	(0.61)			(0.61)	(2.38)				

the feedback generally resulted in decreased $ACRP$ and increased $VCRP$, with differences occurring between the responses of the two age groups due to feedback. The observed effect sizes were large for the significant main and interaction effects (i.e., $\eta_p > 0.14$, Tables 1 to 3) and medium to large for the significant pairwise tests (i.e., $|d| > 0.5$, Tables A.4 to A.6), supporting both of our hypotheses.

Specifically, the lower values of $ACRP$ for thigh-shank at PTE, TO (terminal stance), and HS (terminal swing), and for shank-foot at PTE suggest a decrease in the available degrees of freedom of the lower limb segments. During late stance (PTE and TO), this trend may reflect the effort of the walkers to increase their leg extension, which is also associated with increased propulsive force (Peterson et al., 2010; Hsiao et al., 2015), thus resulting in longer strides in the FB condition. A tighter coupling of the shank-foot pair was also found in research examining people with osteoarthritis (Wang et al., 2021c), where a reduced shank-foot $ACRP$ was associated with delaying heel-off. In our work, delaying heel-off would be a necessary mechanism to achieve the increased thigh extension, and, consequently, generation of a longer stride length.

Previous work has found that thigh-shank $ACRP$ is lower when walking on a treadmill at a fast self-selected speed compared to the normal speed (Ghanavati et al., 2014), and we also observed a decrease in this parameter when comparing N and F during toe-off. Interestingly, there were also differences between F and FB, despite similar normalized walking speeds in these conditions (an average of 0.98 in F and 0.95 in FB, Table 1). Indeed, the thigh-shank $ACRP$ was lower in all three windows examined during the feedback condition, which is indicative of the different coordinative functions elicited by feedback compared to fast walking. In summary, the results support the hypothesis that providing feedback affected $ACRP$.

Examination of the effect of age on $ACRP$ found a significant difference between the age groups only for shank-foot in the FB condition at PTE, with the young adults recording a lower $ACRP$ compared to the older adults (Fig. 3). This is similar to the previous findings of differences in shank-foot coordination between young and older adults during the stance phase of gait, which could result in smaller ankle propulsive power in the older walkers (Hafer and Boyer, 2018). In the current study, the impact of lower propulsion can be seen in shorter stride lengths of the older adults in the FB walking condition compared to the young participants. These results support our hypothesis that the coordination changes as a result of haptic feedback could be a function of the age of the participant.

Coordination variability has been taken as an index of neuromuscular system adaptability as new movement strategies are explored in response to perturbations. Consistent with this interpretation, higher variability has been observed in runners with more experience (Mo and Chow, 2019; Wang et al., 2021b), in response to conditions such as fatigue (Chen and Chou, 2022), knee osteoarthritis (Wang et al., 2021c), and walking on slopes (Dewolf et al., 2020) or uneven surfaces (Ippersiel et al., 2022). We found that $VCRP$ was larger when feedback was available compared to normal walking and, in certain cases, larger than fast walking. This implies that providing haptic feedback prompted the search for different approaches to achieve the goal of increased thigh extension, resulting in variability in the CRP patterns. In particular, $VCRP$ of thigh-shank in the feedback condition was larger during PTE and TO compared to both normal and fast walking, pointing to the effort to explore different patterns of coordination of these two segments to reach the thigh extension target. It is interesting to note that while previous work has found lower variability with increased walking speeds (Abbasi et al., 2020), in the present study, the variability in the FB condition was larger than fast walking, despite similar normalized speeds (Table 1). These results provide evidence for the unique role the haptic feedback had in altering leg coordination variability in gait, as we hypothesized.

Examination of the effect of age on coordination variability revealed higher $VCRP$ in the FB condition compared to the N and F conditions in young adults but not older adults. The absence of a pronounced difference in variability in the different walking conditions of older adults, and the lower values of the shank-foot $VCRP$ of that age group compared to the young-adult walkers at TO in the FB trial (Fig. 3), may reflect a more cautious approach in responding to the feedback. Previous research that found lower variability in older adults (Hafer and Boyer, 2018) suggested that it may stem from possible limitations of the muscular system in that age group or from efforts to maintain dynamic balance and reduce the risk of falling (Chiu and Chou, 2013).

The current work has some limitations. The number of male and female participants was not equal, and sex might be a confounding factor. However, previous work that examined the effect of sex on CRP during walking did not find a difference between the male and female subjects (Hoolihan et al., 2023). While the thresholds used to interpret the effect sizes have been employed in previous research (Huang et al., 2020; Hoolihan et al., 2023), future meta-analyses focusing on CRP could provide more accurate estimates. Although this work has revealed valuable information regarding the effect of haptic feedback on lower-limb coordination, further work should examine feedback-driven coordination changes in planes other than the sagittal. Such work should also consider how behavioral information regarding the lower limbs might influence coordination patterns in the upper extremities.

5. Conclusion

As a window into the adaptive strategies of the neuromuscular system, this work investigated the coordination of thigh-shank and shank-foot segments in response to haptic feedback designed to increase thigh extension. With the provision of such feedback, the movement of the lower limbs became more in-phase while coordination variability increased. Additionally, we observed differences in coordination between young and older adults as a result of the feedback. These results pave the way for future research studying the impact of gait training using haptic feedback on limb coordination and the stability of such coordination.

CRediT authorship contribution statement

Mohsen Alizadeh Noghani: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Ehsan Sharafian M.:** Writing – review & editing, Formal analysis. **Ben Sidaway:** Writing – review & editing, Conceptualization. **Babak Hejrati:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no financial and personal relationships with other people or organizations that could have inappropriately influenced the work reported in this paper.

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Appendix. *p*-Values and effect sizes of pairwise comparisons

See Tables A.4–A.6.

Table A.4
The point estimates of Cohen's d, their 95% confidence intervals, the corresponding interpretations, and the p-values for the significant pairwise comparisons of Table 1 (ANOVA results for the spatiotemporal parameters). YA and OA refer to the young adult and older adult groups, respectively. A negative value of d indicates the first condition of the pair had a smaller mean, while a positive value signifies that the first condition of the pair had a larger mean.

Parameter	Pair		p	d	95% CI	Interpretation
θ_{PTE}	N	F	0.002	−0.94	(−1.46, −0.40)	Large
	N	FB	<0.001	−1.42	(−2.04, −0.79)	Large
	F	FB	<0.001	−1.15	(−1.71, −0.57)	Large
	FB-YA	FB-OA	<0.001	1.92	(0.83, 2.98)	Large
Stride length (height-normalized)	N	F	<0.001	−2.25	(−3.07, −1.40)	Large
	N	FB	<0.001	−1.85	(−2.57, −1.11)	Large
	F	FB	<0.001	−1.12	(−1.67, −0.55)	Large
	FB-YA	FB-OA	0.004	1.46	(0.45, 2.44)	Large
Speed (height-normalized)	N	F	<0.001	−2.33	(−3.17, −1.46)	Large
	N	FB	<0.001	−1.26	(−1.84, −0.66)	Large
Cadence	N	F	<0.001	−1.70	(−2.38, −1.00)	Large
	N	FB	0.019	0.52	(0.05, 0.99)	Medium
	F	FB	<0.001	1.37	(0.75, 1.98)	Large
	FB-YA	FB-OA	0.012	−1.24	(−2.19, −0.26)	Large

Table A.5
The point estimates of Cohen's d, their 95% confidence intervals, the corresponding interpretations, and the p-values for the significant pairwise comparisons of Table 2 (ANOVA results for $ACRP$). YA and OA refer to the young adult and older adult groups, respectively. A negative value of d indicates the first condition of the pair had a smaller mean, while a positive value signifies that the first condition of the pair had a larger mean.

Window	Pair		p	d	95% CI	Interpretation
PTE (T-S)	N	FB	<0.001	0.56	(0.08, 1.03)	Medium
	F	FB	0.006	0.79	(0.27, 1.28)	Medium
	YA	OA	0.016	−0.69	(−1.21, −0.16)	Medium
PTE (S-F)	N	F	<0.001	1.07	(0.51, 1.61)	Large
	N	FB	0.003	0.79	(0.28, 1.29)	Medium
	N-YA	F-YA	0.031	0.78	(0.05, 1.47)	Medium
	N-YA	FB-YA	0.002	1.20	(0.36, 2.0)	Large
	N-OA	F-OA	0.004	1.49	(0.56, 2.39)	Large
	FB-YA	FB-OA	0.035	−1.02	(−1.95, −0.07)	Large
TO (T-S)	N	F	0.03	0.65	(0.16, 1.13)	Medium
	N	FB	<0.001	1.46	(0.81, 2.08)	Large
	F	FB	0.013	0.72	(0.22, 1.21)	Medium
	YA	OA	0.004	−0.77	(−1.29, −0.24)	Medium
HS (T-S)	N	FB	<0.001	1.33	(0.71, 1.92)	Large
	F	FB	0.021	0.70	(0.20, 1.18)	Medium
	YA	OA	0.012	−0.88	(−1.41, −0.35)	Large
HS (S-F)	YA	OA	<0.001	1.21	(0.65, 1.76)	Large

Table A.6
The point estimates of Cohen's d, their 95% confidence intervals, the corresponding interpretations, and the p-values for the significant pairwise comparisons of Table 3 (ANOVA results for $VCRP$). YA and OA refer to the young adult and older adult groups, respectively. A negative value of d indicates the first condition of the pair had a smaller mean, while a positive value signifies that the first condition of the pair had a larger mean.

Window	Pair		p	d	95% CI	Interpretation
PTE (T-S)	N	FB	0.027	−0.64	(−1.12, −0.15)	Medium
	F	FB	0.013	−0.67	(−1.15, −0.18)	Medium
TO (T-S)	N	FB	0.004	−0.81	(−1.31, −0.29)	Large
	F	FB	0.020	−0.60	(−1.07, −0.11)	Medium
	N-YA	FB-YA	0.003	−1.02	(−1.78, −0.23)	Large
	F-YA	FB-YA	0.002	−1.14	(−1.92, −0.31)	Large
TO (S-F)	N	FB	<0.001	−0.91	(−1.42, −0.37)	Large
	N-YA	FB-YA	<0.001	−1.50	(−2.40, −0.56)	Large
	F-YA	FB-YA	0.005	−1.43	(−2.30, −0.51)	Large
	FB-YA	FB-OA	0.035	1.02	(0.07, 1.95)	Large
HS (T-S)	N	FB	0.006	−0.78	(−1.27, −0.27)	Medium
	N-YA	FB-YA	0.005	−1.49	(−2.39, −0.55)	Large
	F-YA	FB-YA	0.02	−1.05	(−1.82, −0.25)	Large

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