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Running head: COORDINATION DURING GAIT IN ELDERLY WOMEN

A Comparison of Gait Patterns between Young and Elderly Women: An Examination of Coordination

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Abstract

This study investigated intralimb coordination during walking in Young and Elderly women using the theoretical model of dynamical systems. Twenty females, ten Young (M age = 24.6 yrs, SD = 3.2 yrs), and ten Elderly (M age = 73.7 yrs, SD = 4.9 yrs), were videotaped during free speed gait and gait perturbed by an ankle weight. Two parameters, one describing the phasing relationship between segments (mean absolute relative phase) and the other the variability of this relationship (deviation in phase), were calculated from the kinematics. Two-way ANOVA (age and weight) with repeated measures on weight indicated that during the braking period the weight increased the mean absolute relative phase between the shank and the thigh and decreased it between the foot and the shank. The Elderly women had significantly smaller values for the mean absolute relative phase between the shank and the thigh during the braking period. For the same period, deviation in phase increased for the segmental relationship between the shank and the thigh. The findings suggest that changes in intralimb coordination take place due to asymmetrical weighting and the aging process. These changes are mostly present during the braking period.

A Comparison of Gait Patterns between Young and Elderly Women: An Examination of Coordination

While walking may be perceived to be a simple task by healthy individuals, the motor control required is complex. With aging, older adults adapt their walking pattern toward a safer, more stable gait (Winter, Patla, Frank, & Walt, 1990; Judge, Davis, & Ounpuu, 1996; Maki, 1997). However, a significant percentage of elderly persons are victims of falls every year, which typically occur during normal activities such as walking (Woollacott & Tang, 1997).

Changes in gait parameters have been reported in healthy older adults (Himann, Cunningham, Rechnitzer, & Patterson, 1988; Winter, et al., 1990; Feltner, MacRae, & McNitt-Gray, 1994; Bohannon, Andrews, & Thomas, 1996). When compared to young adults, older adults have decreases in gait velocity, step length, stride length and single leg support time (Himann, et al., 1988; Winter, et al., 1990; Feltner, et al., 1994; Bohannon, et al., 1996). Reduced pelvic rotation, hip flexion/extension, and ankle plantar flexion during gait are frequently observed in healthy older adults (Murray, Kory, & Clarkson, 1969). The majority of these studies of healthy elderly focus on kinematic changes, with less attention toward the study of coordination.

Coordination is the process by which movement components are organized in time and in sequence to produce a functional movement pattern (Bernstein, 1967; Scholtz, 1990). Coordination between the thigh, shank, and foot segments is needed for a normal gait. In motor control research, stable coordination patterns have been considered a fundamental feature of consistent, functional action (Bernstein, 1967; Clark & Phillips, 1993; Kelso, 1995). A contemporary approach to understand the construction of, and subsequent change in, patterns of coordination comes from the theory of dynamical systems (Clark & Phillips, 1993; Kelso, 1995). In this theory, coordinated patterns are assumed to be constructed out of the constraints applied to the neuromotor system. These constraints come from the organism (e.g., strength limits, joint flexibility, perceptual abilities), the environment (e.g., walking with or without an added ankle weight), and the task (e.g., walking at slow or fast speeds). These constraints effectively reduce the number of degrees of freedom and simplify the management of the neuromotor system, with the motor output being shaped by the constraints applied to the system. This approach to movement coordination contrasts with others, such as the motor program theory, that suggest all the details for the execution of movement are specified a priori by an action plan in the central nervous system.

The dynamical systems theory proposes that change from one coordinated motor pattern (called also an attractor), to a different pattern is discontinuous and occurs when a variable to which the neuromotor system is sensitive is scaled up or down through a critical threshold. This variable is called the control parameter and changes in its value cause the neuromotor system to move between different attractors (Clark & Phillips, 1993; Kelso, 1995). For example, the transition between walking and running is accomplished when the control parameter of speed is scaled up or down (Diedrich & Warren, 1995).

Attractors can be categorized as point, periodic or limit cycle, and chaotic. The limit cycle has been suggested (Schmidt, Treffner, Shaw & Turvey, 1992) as the attractor that can describe the oscillatory motion of the limbs during gait. Based on the dynamical system theory, there are three intrinsic properties that describe the behavioral dynamics of coupled limit cycle attractors: phase locking, entrainment, and structural stability (Clark & Phillips, 1993). Phase locking is defined as the fixed timing or phasing relationship between limit cycles. In other words, how the motion of the two segments is coupled in performing a task. An example of phase locking with respect to gait would be the phasing relationship between the thigh and the shank or the shank and the foot (Diedrich & Warren, 1995). Entrainment is defined as the interaction between limit cycles where possible phase shifts will occur associated with discontinuity. It describes the highly variable phase when the phasing relationship between two segments is about to transition to a new motor pattern. For example, when a walking gait pattern is altered by increased speed it transitions to a running pattern. This transition is also marked by a change in the phasing relationship between the thigh and shank, and also between the shank and foot (Diedrich & Warren, 1995). Structural stability is defined as the ability of limit cycles to stay within their preferred phase locking relationship. In reference to the gait pattern, it reflects how stable (or variable) the phasing relationship of the two interacting segments remains.

To understand the adaptation to changing task demands, the functional patterns of coordination in the lower extremity should be studied for signs of instability. Studying changes in coordination due to the aging process can be used to establish a baseline pattern for a healthy aging population, used for purposes of comparison with common gait pathologies in the elderly population. Additional comparisons of the characteristics of gait coordination in healthy young women with healthy elderly women are necessary because women constitute a majority of the over 60 years age group and gait related disabilities comprise a major portion of geriatric rehabilitation.

The purpose of this study was to describe and to compare the intralimb lower extremity coordination between Young and Elderly women during free speed gait and gait perturbed by an added ankle weight. To accomplish this, the dynamical systems theoretical framework was used. Thus, the motions of the foot, shank, and thigh were modeled as limit cycles and the intralimb coordinative relationships between these segments were investigated. Walking was viewed as an attractor state. The added ankle weight was used as a possible control parameter that tended to move the system toward a new unstable state. Based on this model, we tested the following hypotheses. When the system is under normal conditions (non-weighted free-speed gait), the system will be more stable. However, the Young women will have greater stability and different phasing relationships than the Elderly. In addition, the intralimb coordination will be less stable in both groups when the control parameter (ankle weight) is introduced. These stability changes will be more evident in the Elderly women.

Method

Participants

Ten healthy Young (M age = 24.6 years, SD = 3.2 years; M height = 1.6 m; SD = 0.1 m; M mass = 62.2 kg, SD = 9.8 kg) and ten healthy Elderly (M age = 73.7 years; SD = 4.9 years; M height = 1.61, SD = 0.04 m; M mass = 63.1, SD = 5.5 kg) women participated. All provided informed consent. Women were selected because they constitute the majority of the population over 60 years old. The Young subjects were recruited from the University of Nebraska at Omaha campus population, while the Elderly subjects were recruited from surrounding community senior wellness organizations in the Omaha area. All subjects were recruited through word of mouth. The participants did not have any clinical history of musculoskeletal and/or neurological problems. Both groups reported participation in moderate physical activity for 30 minutes per day, three to five times per week.

Instruments

There were two conditions: subjects walking with and without an ankle weight. Kinematic data for the right lower extremity were collected from the sagittal view using a high speed (60 Hz) camera (Panasonic WV-CL350) interfaced to a high speed video recorder. Prior to videotaping, reflective markers were placed on the right lower extremity to identify the following landmarks: a) right head of the fifth metatarsal, b) right heel underneath the calcaneus, c) right lateral malleolus, d) right lateral joint line of the knee, and e) mid-point of the thigh segment, identified as the segment between the right greater trochanter of the femur and the right lateral joint line of the knee (Figure 1). Joint markers were digitized using the Motus 4.0 system (Peak Performance Technologies, Inc., Englewood, CO). The kinematic positional coordinates of the sagittal markers were scaled and smoothed using a Butterworth Low-pass Filter with a selective cut-off algorithm (Jackson, 1979). The cut-off frequency values used were 6-10 Hz.

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INSERT FIGURE 1 ABOUT HERE

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<u>Protocol</u>

Subjects were asked to wear shorts to ensure visibility of the reflective markers and their normal sport shoes to assure their normal performance. Walking speed was monitored over a three meter interval using a photo-electronic timing system comprised of two infrared timing lights connected to a digital timer. Subjects were given time to accommodate to the experimental set-up prior to testing. The walking distance for each trial was approximately 15 meters. During the accommodation time, the subject established a comfortable walking pace that was identified by the timing system and recorded by the investigator. This speed (+/- 5%) was used for the subsequent testing, and a trial was considered acceptable only when the walking speed was within this range. In the present study, the Young group walked at an average pace of 1.43 m/s, while the Elderly group walked at an average pace of 1.24 m/s.

Every subject walked at the previously established self-selected pace with and without an ankle weight (Keiser, Model 60-0863) equal to 5% of the subject's body weight attached to the right limb. Each condition consisted of ten acceptable trials, for a total of 20 trials per testing session. The 5% of body weight was selected through pilot work and previous literature (Thelen, Fisher, Ridley-Johnson, 1984; Jones, Knapik, Daniels, Toner, 1986; Graves, Martin, Miltenberger, Pollock, 1988; Skinner & Barrack, 1990; Clark & Phillips, 1993). In addition this type of perturbed gait has clinical relevance. Limb weighting has been used as therapeutic intervention to decrease unwanted limb movement and improve stability (Hewer, Cooper, Morgan, 1972; Morgan, 1975).

However, asymmetrical limb weighting may also cause a sudden change in the mechanics of the human-limb weight system which will affect the stability and may increase the risk of fall.

Data Analysis

From the plane coordinates obtained, the sagittal foot, shank, and thigh, angular displacements and velocities were calculated (Figure 1). Angular displacement data were differentiated using a cubic spline routine to calculate angular velocities. All kinematic angular displacements and velocities were normalized to 100 points for the stance period using a cubic spline routine.

The stance period for each trial was divided into two periods: the braking period and the propulsive period using the anterior posterior ground reaction force. The force data were collected simultaneously with the kinematics but are not presented in this paper. Separate examination of each period was made since measurements over the entire stance can mask differences for a single period.

To examine intralimb coordination, phase portraits for the foot, shank and thigh were generated. The phase portrait analysis follows Rosen's (1970) suggestion that the behavior of a dynamical system may be captured by a variable and its first derivative with respect to time. After the phase portraits were constructed, the resulting phase plane trajectories were transformed from Cartesian (θ, ω) to polar coordinates, with a radius and phase angle

$\Phi = \tan^{-1}[\omega/\theta]$ (Rosen, 1970).

The phase angles of the segments' trajectories were used to examine phase relationships. During walking, the foot and the shank segments could be viewed as rotating about the axis of the ankle joint (Scholtz, 1990; Clark & Phillips, 1993), while the shank and the thigh segments could be viewed as rotating about the axis of the knee joint. Relative phase represents the phase relationships or coordination between the actions of the two interacting segments at every point during a specific time period. Essentially, it depicts how the two segments are coupled in their movements while performing the task. Relative phase was calculated throughout the stance period of walking by subtracting the phase angles of the corresponding segments: Φ[Relative phase of ankle] = Φ[Foot] - Φ[Shank] and Φ[Relative phase of knee] = Φ[Shank] - Φ[Thigh]. Values close to zero degrees indicate that the two segments are moving in a similar fashion or in-phase, while values close to 180 degrees indicate that the two segments are moving in opposite directions or out-of-phase. The curves for relative phase of each segmental relationship were averaged across trials to generate mean ensemble curves for both conditions for each subject.

To test differences between relative phase curves, it was necessary to collapse and characterize the curves by single numbers (Winter, 1984; Sidaway, Heise, & Schoenfelder-Zohdi, 1995; Van Emmerik & Wagenaar, 1996; Hamill, Van Emmerik, Heiderscheit, & Li, 1999; Stergiou, Jensen, Bates, Scholten, Tzetzis, 2001), therefore, two additional parameters were calculated from the mean ensemble curves.

The first parameter was defined as the mean absolute relative phase (Stergiou, Jensen, Bates, Scholten, Tzetzis, 2001). It was calculated by averaging the absolute values from all the points of the mean ensemble curve for the two designated periods (braking and propulsion). A low value indicates a relationship between the two segments' movements that is more in-phase. The second parameter was defined as the deviation in phase (Van Emmerik & Wagenaar, 1996; Hamill, Van Emmerik, Heiderscheit, & Li, 1999; Stergiou, Jensen, Bates, Scholten, Tzetzis, 2001). It was calculated by averaging the standard deviations from all the points of the mean ensemble curve for the two designated periods. A low value indicates a more stable (less variable) relationship between the two segments' movements. Lastly, group means were also calculated for both parameters for each segmental relationship, for each period, and for each condition.

Statistical Treatment

A two by two mixed (age by ankle weight) ANOVA with the weight as the repeated factor was performed on the subjects’ means for the mean absolute relative phase and for the deviation in phase. Statistical analysis was performed for each coordinative relationship (foot-shank and shank-thigh) and for each period (braking and *propulsion*). A Tukey multiple comparison post-hoc analysis was used when there was a significant F-ratio ($p < .05$). Effect sizes were also calculated (Cohen, 1988).

Results

The results of the group analysis are presented in Table 1. For the mean absolute relative phase, the application of the ankle weight significantly increased these values for the relationship between the shank and thigh during the braking ($F(1,18) = 14.3$, $p<.01$, $f = 0.81$) and the propulsion period ($F(1,18) = 5.0$, $p<.05$, $f = 0.45$). However, the application of the ankle weight significantly decreased the mean absolute relative phase values for the relationship between the foot and shank during the braking period ($F(1,18) = 10.2$, $p<.01$, $f = 0.47$). Age was significant for only one relationship. When compared to the Young group, the Elderly group had smaller mean absolute relative phase values for the relationship between the shank and the thigh during the braking period ($F(1,18) = 6.5$, $p<.05$, $f = 0.94$). No significant interactions were found.

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For deviation in phase, the application of the ankle weight significantly increased these values for the relationship between the shank and thigh during the braking period ($F(1,18) = 4.6$, $p<.05$, $f = 0.57$). It is interesting to notice (Table 1) that the ankle weight produced a non-significant increase in deviation in phase during both segmental relationships across both periods and for both groups. No other significant results were found.

The phase portraits of the individual segments, analyzed for representative subjects from both groups, are presented in Figures 2 and 3. The direction of movement for all trajectories is clockwise. Typical analysis of phase portraits is directed toward the shape of the graphs, rather than the precise values represented (Winstein & Garfinkel, 1989). Functionally, every time the trajectory crosses zero, a segmental reversal occurs (as velocity is equal to zero), such as is shown for the thigh segment during propulsion. The graphs representing the foot or the shank segments are similar, regardless of age or weight condition. Upon examination of the thigh segment during the braking period, dissimilarities can be observed between the Young and the Elderly (Figure 3). The Elderly group had several cusps pointing toward zero velocity, which suggest a sudden interruption of movement. Such interruptions are caused by sudden cessation of forces opposing motion and/or the sudden resumption of motion (Weinstein & Garfinkel, 1989).

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INSERT FIGURES 2 AND 3 ABOUT HERE

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The coupling of the segments was examined using the relative phase curves for the same representative subjects from both groups (Figures 5 and 6). Such a graphical evaluation assists in verifying the statistical results presented above. In addition, it helps in understanding the actual coupling of the segments during walking. The general configurations of these curves are similar between the Young and the Elderly group for both segmental relationships, regardless of timing period. However, dissimilarities can be seen during the braking period. For the relationship between shank and thigh the relative phase curves for the Elderly group are more in-phase (closer to zero and smaller in values) for both conditions. This observation confirms the statistical result that the Elderly group had significantly smaller mean absolute relative phase values for this relationship during the braking period. During the braking period, the relationship between shank and thigh began with negative values, indicating that the thigh is leading the shank. About halfway through the braking period, the relative phase curve passes through zero, indicating a more in-phase relationship between the segments. The relative phase values continue to increase, as the shank now leads the thigh for the remainder of the period. The segmental relationship between the foot and shank for the braking period begins in a more in-phase fashion than that for the shank and thigh. The relative phase curve begins near zero, and then takes on a relatively sharp rise until about halfway through the period. At this point, the curve makes a small decline followed by a plateau. For the propulsion period, the two segmental relationships are nearly opposite. The shank and thigh relationship begins in-phase, but gradually shifts to a more out-of-phase movement pattern, with the thigh leading the shank virtually throughout the entire period. The foot and shank relationship, however, begins more out-of-phase, then gradually shifts to a more in-phase pattern. This indicates that the foot leads the shank.

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INSERT FIGURES 4 AND 5 ABOUT HERE

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Discussion

Research in the area of segmental coordination during gait is limited, with few studies related specifically to coordination in the elderly. The purpose of this study was to use the dynamical systems theory to describe and to compare the intralimb lower extremity coordination between Young and Elderly women during free speed gait and gait perturbed by an added ankle weight.

In the present work, the phasing relationship of limb segments (relative phase) within the same leg was used as the order parameter. Based upon the literature (Scholtz, 1990; Clark & Phillips, 1993; Kelso, 1995), relative phase was used because it incorporates both the periodic and the coupling motion of the segments involved. An added ankle weight was proposed as possible control parameter on the premise that any change of coordination due to the added weight may lead to an unstable gait pattern. Thus, the order parameter of relative phase was examined for changes caused by the control parameter. The relative phase curves were described in terms of mean absolute relative phase and deviation in phase to allow for statistical comparisons.

Regarding the mean absolute relative phase, small values indicate that the two segments are moving in a similar fashion or in-phase, while large values indicate that the two segments are moving in opposite directions or out-of-phase. For deviation in phase, small values indicate a more stable (less variable) relationship between the two segments' movements, while large values indicate an unstable relationship.

Differences in mean absolute relative phase were found between the Young and Elderly groups for the relationship between the shank and thigh during the braking period of walking. For the Elderly group, these two segments were moving more in-phase during this period. When the weight was introduced, the mean absolute relative phase values increased for the relationship between shank and thigh during the same period, indicating a more out-of-phase relationship between the two segments. A similar result was found for the same segmental relationship during the propulsion period of walking. For the foot and shank relationship, the weight application resulted in reduced mean absolute relative phase values during the braking period of walking, indicating a more in-phase relationship between these two segments during this period.

The behavioral differences between the age groups during the perturbed gait might be due to ankle weakness in the older group. Such weakness has been documented in older adults as an indicator of falls (Whipple, Wolfson, & Amerman, 1987; Thelen, Schultz, Alexander, & Ashton-Miller, 1996). The older adults may have more difficulty in adapting to the effect of the control parameter, thus eliciting a larger change in behavior. Furthermore, the larger effect of the control parameter was found during the braking period. During this period, the added mass made it difficult to control the forward motion of the body.

This conclusion is supported by the results from the deviation in phase. The application of the ankle weight significantly increased the deviation in phase for the relationship between the shank and thigh during the braking period of walking. This suggests an increase in variability and thus, a less stable relationship between the two segments during this period.

The phase portraits gave additional insight into coordination. A phase portrait identifies interruptions in coordination more easily by providing a picture of the resultant action of the control mechanisms (i.e., muscular system, nervous system). Changes were more evident in the phase portrait of the thigh segment of the Elderly group, especially during the braking period, indicating that coordination changes occurred upon addition of the weight. This observation supports the statistical results and the conclusions made above.

The fact that the other phase portraits were relatively similar suggests that there were no other age-related differences or that an examination of just the individual segments and not their coupling was not sensitive for detecting changes in coordination, especially, when the system has not transitioned into a new attractor state. With or without the weight all subjects remained within the same behavior or attractor state (i.e., walking). Thus, changes in coordination can be better detected by examining the coupling of segmental actions (i.e., relative phase).

The use of phase portraits and relative phase curves allowed for the incorporation of both angular position and velocity to examine coordination and movement. Functionally, this approach has an advantage because there is evidence that receptors exist within the muscles and tendons controlling for both position and velocity (McCloskey, 1978). Winstein and Garfinkel (1989) also suggested that a phase plane analysis can be used to describe movement and also provide a window into control processes.

A possible limitation of the present study was that only one weighted condition was used. Using multiple weight conditions will ensure transition in behavior. However, it should be mentioned that while weights of 1-3% may also cause changes in kinematic and/or kinetic variables, weights above 5% can definitely have such effect regardless of walking speed (Jones, Knapik, Daniels, Toner, 1986; Miller & Stamford, 1987; Graves, Martin, Miltenberger, Pollock, 1988; Skinner & Barrack, 1990). Thus, the selection of the control parameter used in this study would seem to be one method that would adequately challenge gait.

In summary, differences identified between the Young and Elderly groups suggest that changes in intralimb coordination may take place with the aging process. These differences could serve as a foundation for future prospective studies related to recognizing Elderly individuals where changes in segmental coordination may be a predisposing factor to injurious falls. Following the acquisition of this information, additional studies could then be conducted on how to aid the Elderly in avoiding falls by increasing the stability of the attractor.

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Table 1

Mean absolute relative phase values and deviation in phase values for Young and Elderly women during free-speed weighted and non-weighted conditions

		YOUNG (n = 10)		ELDERLY (n = 10)	
Measures		No weight	Weight	No weight	Weight
Values for Mean absolute relative phase					
Braking					
Shank-Thigh	M	18.92*†	21.06 †	15.08*	18.06
	SD	3.91	3.24	2.58	3.62
Foot-Shank	M	22.76*	22.12	25.40*	23.59
	SD	2.31	2.17	2.90	2.59
Propulsion					
Shank-Thigh	M	59.01*	63.04	57.62*	58.19
	SD	5.02	4.03	5.28	6.07
Foot-Shank	M	11.51	12.24	13.77	13.25
	SD	2.82	2.35	3.31	3.32
Values for Deviation in phase					
Braking					
Shank-Thigh	M	5.18*	5.84	5.49*	6.58
	SD	1.53	3.06	1.51	2.23

(Table continues)

	Foot-Shank	M	4.11	4.34	3.74	4.10
		SD	0.90	1.17	0.54	0.80
Propulsion						
	Shank-Thigh	M	9.74	10.30	7.50	9.99
		SD	5.45	8.79	1.65	2.44
	Foot-Shank	M	2.73	2.86	3.03	3.52
		SD	0.85	0.96	0.85	0.78

* Indicates significant difference ($p < .05$) for the weight factor.

† Indicates significant difference ($p < .05$) for the age factor.

Figure Captions

Figure 1. Identification of the thigh, shank, and foot angles.

Figure 2. Braking Phase Portraits from two representative subjects: (a) Young Unweighted Foot, (b) Young Weighted Foot, (c) Elderly Unweighted Foot, (d) Elderly Weighted Foot, (e) Young Unweighted Shank, (f) Young Weighted Shank, (g) Elderly Unweighted Shank, (h) Elderly Weighted Shank, (i)Young Unweighted Thigh, (j) Young Weighted Thigh, (k) Elderly Unweighted Thigh, (l) Elderly Weighted Thigh. All phase portraits should be read in the clockwise direction.

Figure 3. Propulsion Phase Portraits from the same representative subjects: (a) Young Unweighted Foot, (b) Young Weighted Foot, (c) Elderly Unweighted Foot, (d) Elderly Weighted Foot, (e) Young Unweighted Shank, (f) Young Weighted Shank, (g) Elderly Unweighted Shank, (h) Elderly Weighted Shank, (i)Young Unweighted Thigh, (j) Young Weighted Thigh, (k) Elderly Unweighted Thigh, (l) Elderly Weighted Thigh. All phase portraits should be read in the clockwise direction.

Figure 4. Relative phase curves from the same representative subjects for the braking period. The elderly curves are represented by open circles and the young curves by open squares.

Figure 5. Relative phase curves from the same representative subjects for the propulsion period. The elderly curves are represented by open circles and the young curves by open squares.