

Inter-joint coordination during walking in individuals with post-stroke hemiparesis

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Undergraduate Thesis

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ABSTRACT

Stroke leads to impairments in intra-limb and inter-joint coordination. Measures of inter-joint coordination have been shown to relate with walking function and fall risk post-stroke. Here, our objective was to compare inter-joint coordination in the paretic versus non-paretic lower limb of individuals with post-stroke hemiparesis. Twelve individuals with post-stroke hemiparesis (8 males and 4 females, 42 – 70 years old) and eight able-bodied controls were recruited for the study. Gait analysis was performed during walking on an instrumented treadmill at a self-selected speed. The average coefficient of correspondence (ACC) was used to quantify the consistency of inter-joint coordination during multiple gait cycles. ACCs can range from 0 to 1, with numbers closer to 1 describing perfect stride-to-stride consistency. ACC values for ankle-knee and knee-hip angle-angle data-plots were compared between the paretic versus non-paretic limb post-stroke, between non-paretic limb versus able-bodied controls, and before versus after a gait training intervention. Our results to date show lower ACCs for the paretic versus non-paretic legs in individuals post-stroke for both ankle-knee coordination (0.86 for paretic and 0.93 for non-paretic) and knee-hip coordination (0.87 for paretic and 0.95 for non-paretic). Additionally, ACCs for both the non-paretic and paretic limbs were lower than ACCs demonstrated by able-bodied individuals (>0.98). This study demonstrates deficits in inter-joint coordination in both paretic and non-paretic lower limbs of stroke survivors during walking and takes a step toward understanding the effects of stroke and gait rehabilitation on inter-joint coordination during gait.

Keywords: post-stroke, gait, inter-joint coordination, treadmill training, walking, stroke rehabilitation

Introduction

Gait impairments in individuals with hemiparesis post-stroke span multiple lower limb joints and multiple phases of the gait cycle, contributing to decreased gait speeds, stride length, and show a high correlation with fall risk. [1, 2] These impairments are due, in part, to abnormal joint excursions and deficits in both inter-joint and intra-limb coordination.[3] The goal of gait retraining is to restore normal ambulation in stroke survivors.. Clinical measurements such as step length and walking speed are commonly used in the literature to track the progression of individuals during clinical rehabilitation and to measure the effectiveness of rehabilitation in research studies. [4-7] However, despite the frequent use of measures of clinical function such as gait speed and endurance, clinical tests have several shortcomings. For instance, clinical measures do not identify changes in specific gait biomechanics parameters nor changes in coordination during gait. Further, clinical tests fail to detect changes in different phases of the gait cycle. [3, 4]

In contrast, gait asymmetry, the difference between kinematics and kinetics of the non-paretic and paretic leg, has the potential to provide valuable insights about post-stroke gait deficiencies, despite there being no accepted standard method quantification of inter-limb kinematic asymmetry. [8] Angle-angle plots [3], also referred to as cyclograms. Have been previously used to measure inter-joint coordination. Angle-angle plots are created by plotting the range of motion of one joint during the gait cycle against the values of another joint, and offer a visual representation of inter-joint coordination during the gait cycle using appropriate geometric properties. [9, 10] Moreover, by coupling kinematics of two or more joints, the angle-angle plots reveal new insights about gait impairments beyond those provided by evaluating kinematic variables of a single joint

One mathematical technique used to analyze angle-angle plots is known as the

average coefficient of correspondence (ACC). Developed by Field-Foote et al (2002), ACC was first used to assess inter-joint coordination the lower extremities of individuals with spinal cord injuries. [11] Not only do ACCs provide information about the entire gait cycle, the ACC also allows for evaluating variability across multiple gait cycles simultaneously. Using sagittal plane kinematic data, it is possible to quantify the deficits in post-stroke lower limb motor control and walking using ACCs.

The purpose of this study is to investigate the differences in inter-joint coordination between the paretic and non-paretic legs of individuals post-stroke using ACC and angle-angle plot analysis. While previous studies using ACC post-stroke focused on the hip and knee joints [1,3], our study further examines ankle-knee coordination in both paretic and non-paretic leg. Here, we will calculate hip-knee ACC and knee-ankle ACC to gain a comprehensive understanding of the inter-joint coordination during gait in people post-stroke. We hypothesize that the mean ACC values for both hip-knee and knee-ankle will be lower in the paretic leg than the non-paretic leg.

Methods

Subjects

Twelve individuals with post-stroke hemiparesis (8 male and 4 female, 42 – 70 years old, 60.4 ± 9.3 years old) were recruited to participate in this study. Table 1 displays the clinical characteristics for the individuals post-stroke. The age of the participants ranged from 42 to 70 years old and all had a stroke onset of at least 9 months. In addition to the post-stroke participants, 8 able-bodied individuals were also recruited and used as a control group. Inclusion criteria were the ability to walk 4 minutes on a treadmill at a self-selected speed (with or without handrail support), a

single stroke, more than 6 months post-stroke, and absence of orthopaedic or other conditions that limit walking. Inclusion criteria for the control group were absence of neurologic or orthopaedic diagnoses.

Subject	Gender	Age (years)	Side of Hemiparesis	Stroke Onset (months)	SS Gait Speed (m/s)	SS Treadmi Speed (m/s)	Fast Speed (m/s)
1	M	70.5	Left	43.96	0.90	0.67	0.95-1.05
2	M	60	Left	32	0.38	0.38	0.42
3	M	68	Left	35.6	0.79	0.79	1.01
4	M	42	Left	9.5	0.94	0.61	0.87
5	M	69	Right	50	0.43	0.55	0.8
6	F	60	Right	11	0.69	0.42	0.45-0.57
7	M	66	Right	42	0.79	0.70	1.1
8	F	55	Left	27	--	0.25	0.35-0.4
9	M	59	Left	12	0.33	0.20	0.25
10	F	45	Left	59	0.83	0.25	0.32-0.35

Table 1. Demographic and clinical characteristics of study participants. NOTE: information for two of the participants is not shown

Data Collection

At the beginning of each session, reflective markers were attached to bilateral thigh, shank, and foot segments, as well as the pelvis and trunk. The position of these markers was tracked by seven VICON Motion Capture cameras positioned around the laboratory. A standing calibration was collected. When the calibration was complete, participants were asked to walk on the treadmill to find a comfortable self-selected speed at which the walking trials would be performed. Participants walked at their self-selected speed for 30 seconds. Marker data were captured at 120 Hz. Ground reaction force data were collected at 1000-Hz through force platforms embedded within the treadmill belts (Bertec Inc, USA). Data analysis was performed in Visual 3D (C-Motion Inc, USA). The vertical ground reaction force data were used for event detection (initial contact and toe-off) using a 20-N force threshold. Sagittal plane joint

angles for bilateral hip, knee, and ankle were calculated and exported for further analysis.

Data-analysis for calculation of ACC

The sagittal plane kinematic data (time-normalized to the gait cycle) for bilateral hip, knee, and ankle joints collected were exported into Excel files using Visual3D software. These files were input into a custom MATLAB program developed in the lab for computation of inter-joint coordination. In addition, angle-angle plots for the knee-ankle and hip-knee joints were also produced. Figure 1 shows an example angle-angle plot (right) for a particular subject, obtained by plotting the angle data from the Ankle Angle Plot (top left) against the angle data from the Knee Angle Plot (bottom left).

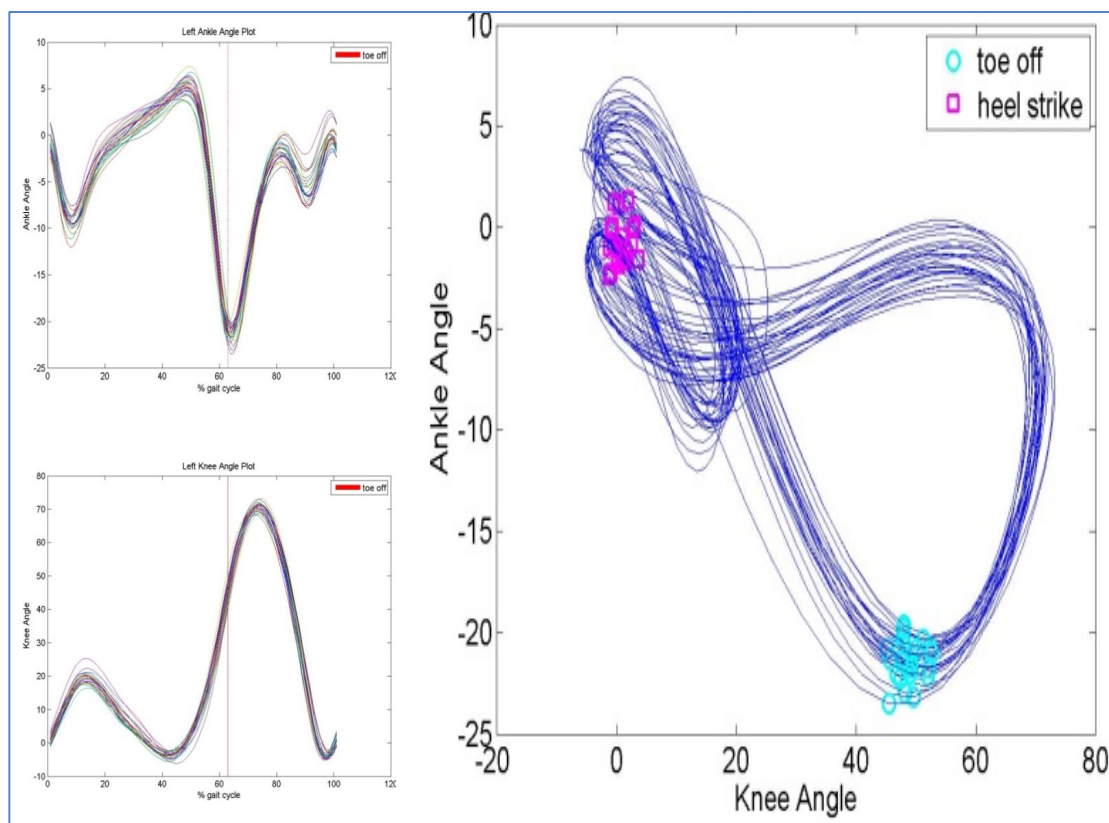


Figure 1. The kinematics (joint angles) obtained at the ankle (top left) and the knee (bottom left) using 3-D gait analysis are plotted across the duration of the gait cycle. Each line within the plots represents an individual gait cycle obtained during a 30 second walking trial. By plotting these ranges against each other, the angle-angle plot of the knee and ankle is obtained (right). The smoothness of the shape of the graph and relative overlap between the gait cycles gives insight about inter-joint coordination of the two joints and the overall ACC for the particular individual.

The metric used to calculate inter-joint coordination is the average coefficient of correspondence, or ACC. Developed by Field-Foote et al (2002), ACC is a vector based method that measures the consistency of the angle-angle inter-joint coordination across multiple gait cycles and ranges from 0 to 1. The closer the ACC value is to 1, the more consistent the strides contained in the angle-angle plot. For every two consecutive points $((x_1, y_1), (x_2, y_2))$ in an angle-angle plot, the magnitude, l , and direction, θ , were determined. ACC ($a_{1,2}$) was calculated using the following equations.

$$(1) \quad l_{1,2} = \sqrt{(x_{1,2})^2 + (y_{1,2})^2}$$

$$(2) \quad \cos \theta_{1,2} = x_{1,2}/l_{1,2} \quad ; \quad \sin \theta_{1,2} = y_{1,2}/l_{1,2}$$

$$(3) \quad \sqrt{(\cos \bar{\theta}_{1,2})^2 + (\sin \bar{\theta}_{1,2})^2} = a_{1,2}$$

The average ACC value of all frames (n) was calculated using equation (4).

$$(4) \quad a_{1,2} + a_{2,3} + a_{3,4} \dots a_{n-1,n}/n = \bar{a}$$

Results

Complete Hip-Knee and Knee-Ankle ACC data were collected for all able-bodied and post-stroke subjects and are summarized in the figures below. Although the data in the stroke paretic and non-paretic groups were derived from the same cohort of individuals, it was assumed that the stroke had altered the functioning of the paretic leg to the point where the two legs of the same post-stroke individual could be considered independent. This was confirmed by two sample t-tests that showed that the two groups were significantly different from each other for knee-ankle and hip-knee ($p < 0.006$). Similarly, because the able-bodied control group had no neurological impairment, it was assumed that the right and the left leg would be nearly identical. This was confirmed by a 2-tailed, paired t-test that showed no

difference in the means between the two legs for either knee-ankle or hip-knee ($p < 0.9$).

Therefore, data from only one leg, the right leg, was included in the figure for that group.

Figure 2 and Figure 3 show the ACC and corresponding angle-angle plots for the Hip-Knee and Knee Ankle joints for a particular Able-Bodied participant and Stroke participant.

Panel A for both figures shows data from the left leg of the Able-Bodied participant, panel B shows the non-paretic, right leg of the Stroke participant, and panel C shows the paretic, left leg of that same Stroke participant.

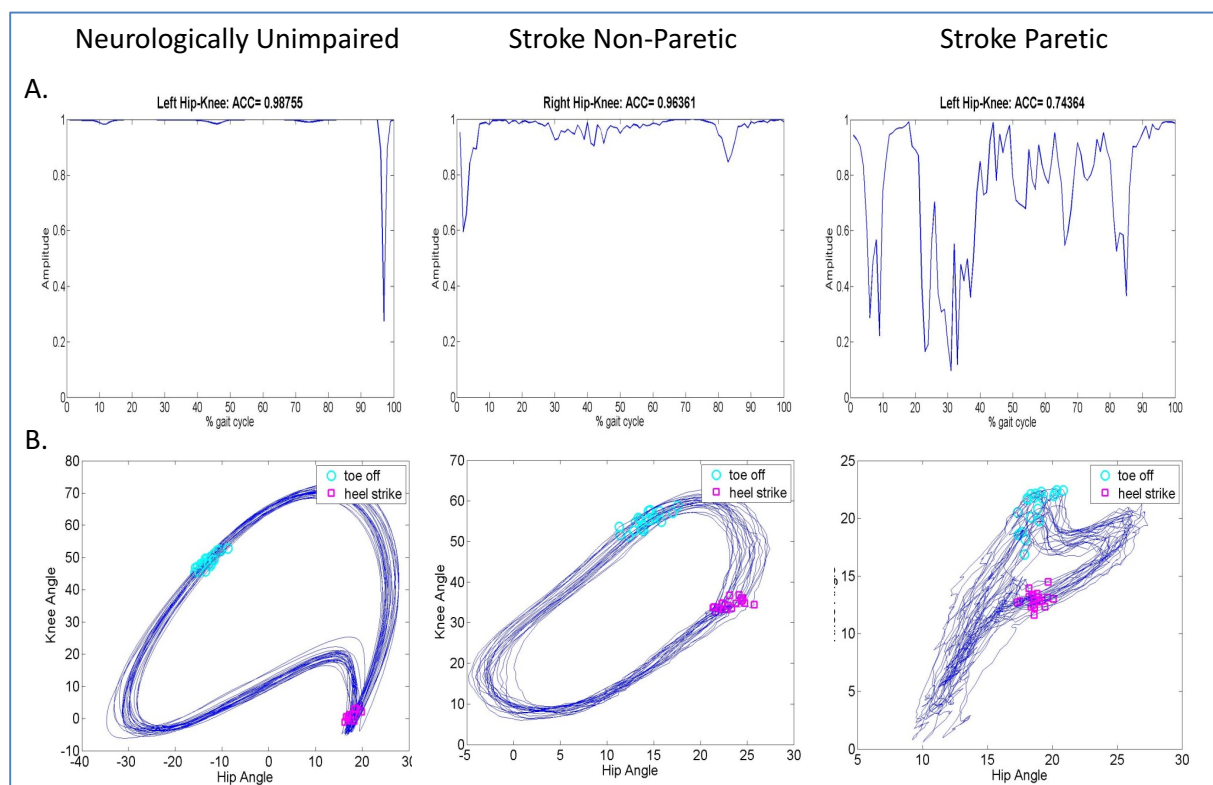


Figure 2. A) Graphical representation of Hip-Knee ACC plotted across the entire gait cycle for a representative Able-Bodied Control subject and a Post-Stroke Subject. B) The corresponding angle-angle plots associated with the ACC plots in A. From left to right, a gradual deterioration of ACC values and inter-joint coordination can be seen in the graphs.

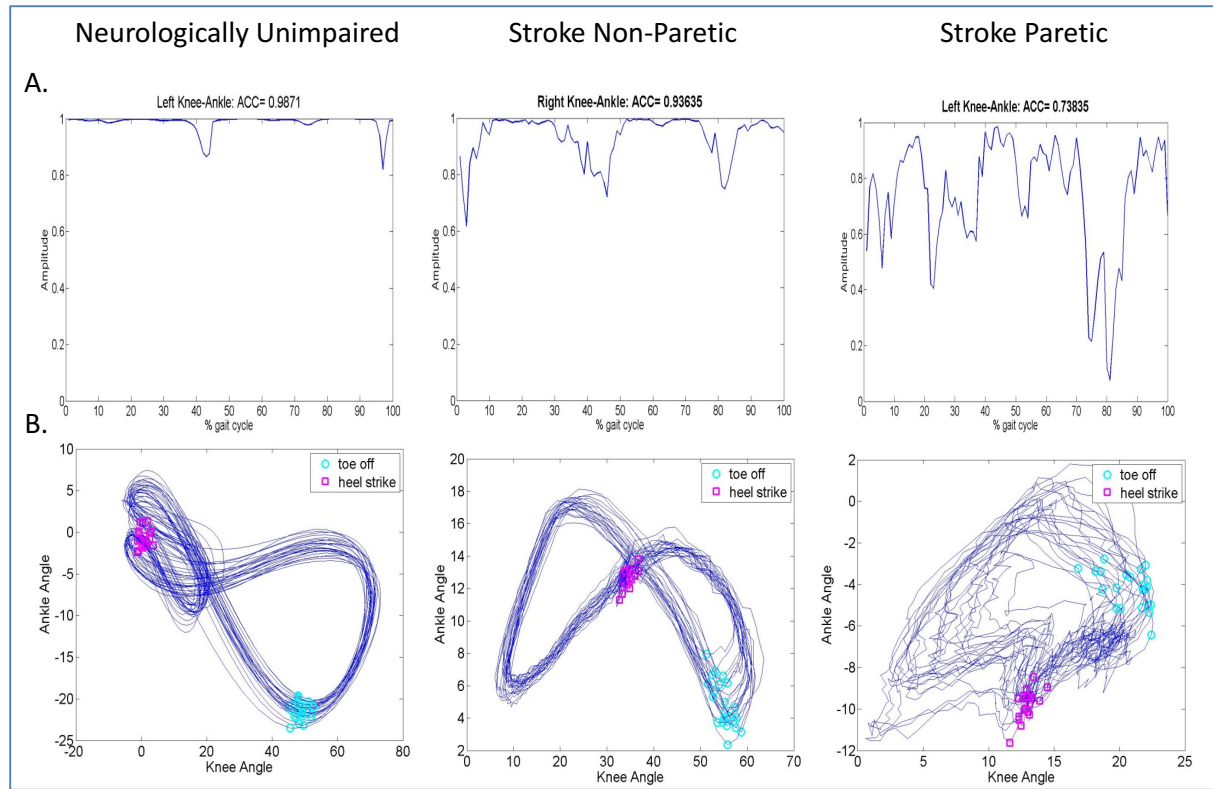


Figure 3. A) Graphical representation of Knee-Ankle ACC plotted across the entire gait cycle for a representative Able-Bodied Control subject and a Post-Stroke Subject. **B)** The corresponding angle-angle plots associated with the ACC plots in A. From left to right, a gradual deterioration of ACC can be seen in the graph's relative proximity to 1. Similarly, the graphs in B) show this trend as the cluster of gait cycles spreads apart and the overall shape diminishes.

The ACC values of the knee-ankle joint of the HYA (0.97 ± 0.02), Stroke-Paretic (0.86 ± 0.09), and Stroke-Non-Paretic groups (0.93 ± 0.03) are shown in Figure 4.A. Similarly, Figure 4.B shows the ACC values of the hip-knee joint for the HYA (0.98 ± 0.02), Stroke-Paretic (0.87 ± 0.07), and Stroke-Non-Paretic groups (0.95 ± 0.03). 1-Way ANOVA tests revealed a significant difference among the three groups for hip-knee ACC ($p = 0.0001$, $F = 12.75$) as well as knee-ankle ACC ($p = 0.001$, $F = 8.92$). Post-hoc comparisons revealed that the ACC values for the hip-knee joints of the Stroke-Paretic group were significantly lower compared to both the Stroke-Non-Paretic group ($p = 0.0026$) and the HYA group ($p = 0.001$). Post-hoc comparisons of the knee-ankle ACC values also produced a similar result. The ACC values for the Stroke-Paretic group were significantly lower compared to both the Stroke-Non-Paretic group ($p = 0.0128$) and the HYA group ($p = 0.0037$).

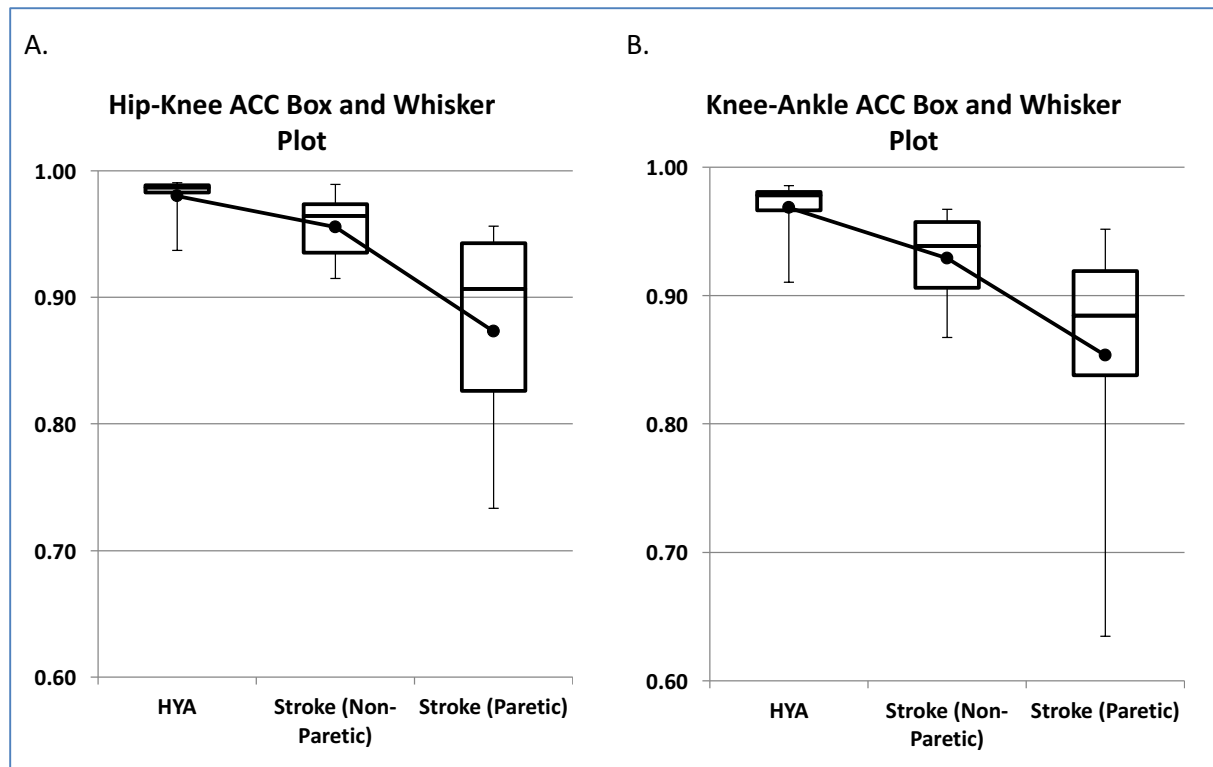


Figure 4. Box and whisker plots for the knee-ankle (A) and hip-knee (B) for the able-bodied control, stroke non-paretic, and stroke paretic are shown above. A One-Way ANOVA was used on each to determine if there was a significant variation in the means of the three groups. The results of the test showed that the stroke paretic group was significantly lower than the other two groups ($p < 0.001$). NOTE: The means are represented by the black dots.

Additionally, ACC values of the Paretic leg for both Hip-Knee and Knee-Ankle were plotted against fast and slow treadmill speeds. These plots, as well as their respective Pearson's Correlation value and p-value are shown in Figure 5. Panel A plots Hip-Knee ACC values against Knee-Ankle ACC values. This correlations produced a significant Pearson's rho of 0.934 ($p\text{-value} < 0.001$). Panels B and D plots the slow treadmill speeds of each participants against Hip-Knee ACC and Knee-Ankle ACC, respectively. Both correlations were significant ($p\text{-value} < 0.01$) and produced Person's rho values of 0.682 and 0.733. Lastly, Panel C plots the fast treadmill speeds of each participants against Hip-Knee ACC.

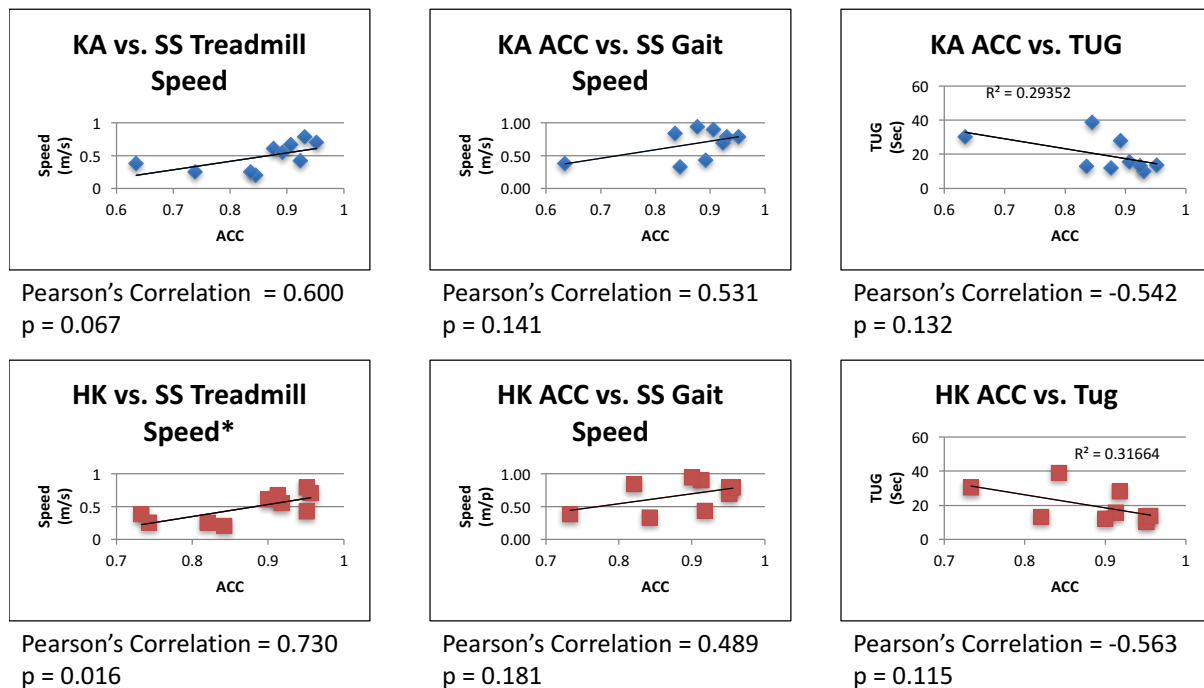


Figure 5. The scatterplots above show ACC values of the paretic leg for the knee-ankle (top row) and the hip-knee (bottom row) plotted against three clinical variables: Self-Selected Treadmill Speed, Self-Selected Gait Speed, and TUG. The Pearson's Correlation value and p-value for each plot are displayed below each plot. Hip-knee ACC showed a significant correlation with SS Treadmill Speed, recording a Pearson's value of 0.730 and a p-value of 0.016.

Discussion

In this study, the inter-joint coordination of the paretic and non-paretic leg of individuals with post-stroke hemiparesis was investigated using the average coefficient of correspondence, or ACC. We hypothesized that the ACC values for the paretic leg would be significantly lower than the ACC values of the non-paretic leg for both the hip-knee and knee-ankle joints. Our results provide strong evidence to support that hypothesis. Additionally, we found a strong correlation between Hip-Knee ACC and the treadmill speed at which a walking trial was conducted.

In previous studies, similar results have been found. [1, 3] Daly et al (2005) used ACC to investigate Hip-Knee coordination. In that study, 35 stroke survivors were recruited, as well as 5 healthy individuals as controls. The results showed the Hip-Knee ACC values in both the paretic and non-paretic legs were significantly different from the control. Similarly,

our results also show that the Hip-Knee ACC values for the paretic leg are significantly different from the control. However, we did not see significance between the non-paretic leg and the control. ACC was used by Lewek et al (2009) during an investigation of the effect of two types of gait training on inter-joint coordination in post-stroke individuals. In total, 19 participants were evaluated. The average ACC values of the hip-knee coordination were (0.79 ± 0.11) for the paretic leg and (0.88 ± 0.10) for the non-paretic leg. Comparatively, the results of the data collected from the 12 post-stroke subjects in this study yield average ACC values of the hip-knee joints of (0.87 ± 0.07) for the paretic leg and (0.95 ± 0.03) for the non-paretic leg. Our reported ACCs are slightly greater than those obtained by Lewek. However, this variation in our results and those of Lewek and Daly could be due to our smaller sample size of $N = 12$. Another factor that may have contributed to the differences is the age-related differences relating to our young control group and the post-stroke group. [12] Walking speed is also known to have an influence on inter-joint coordination, [13] which was also seen in Figure 5. In the future, we plan on using the knowledge obtained from this study to investigate the changes in inter-joint coordination following multiple sessions of gait retraining to better track the progression of a patient through therapy.

Conclusion

The purpose of this study was to investigate the inter-joint coordination between the paretic and non-paretic leg in post-stroke gait. The results demonstrate that in individuals with post-stroke hemiparesis, the ACC of the paretic leg is significantly lower than the ACC of the non-paretic leg for both knee-ankle and hip-knee coordination. Furthermore, significant correlations can be seen between the self-selected treadmill speed that each subject chose and the resulting ACC value for factors as well. Future studies of this work will

be aimed at assessing the effects of gait speed and retraining on the outcome of the ACC value.

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