

Research Article

Three-Dimensional Gait Analysis in a Healthy Geriatric Cohort

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Keywords: Geriatric gait, Gait analysis, Lower extremity motion

<https://doi.org/10.60118/001c.29501>

Journal of Orthopaedic Experience & Innovation

Vol. 2, Issue 2, 2021

Introduction

Three-dimensional gait analysis assesses multiple parameters of lower extremity motion. Neither normative gait patterns nor an understanding of how health and demographic factors impact gait have been established for the geriatric population.

Methods

A single time-point observational study from October 2013 to February 2015 recruited 25 healthy geriatric participants within three cohorts: 60-69, 70-79, and 80 years-old and older. Participants underwent static lower extremity range of motion assessment and gait analysis to collect lower extremity joint kinematics, joint kinetics, and spatiotemporal data. Questionnaires and tools included: FRAX, SF-12, and Fried Frailty Index. Data was compared with non-geriatric controls with mature gait patterns.

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Results

Mean age was 72(SD 8); 44% women. Significant kinematic differences between the geriatric volunteers and controls were observed. Minimum hip flexion was 1.6° (SD 11.9) versus -6.0° (SD 6.9) in controls. Minimum to maximum ankle dorsiflexion was -13.1° (SD 6.3) to 15.8° (SD 3.1) and -21.6° (SD 9.0) to -13.1° (SD 6.3) in controls. Maximum ankle dorsiflexion was significantly different across age cohorts (60-69, 70-79, 80+ respectively): 15.8° (SD 2.9), 13.9° (SD 3.1), 18.0° (SD 1.6). Minimum hip flexion and minimum knee flexion were significantly higher at older ages: 5.7° (SD 7.7) and 9.4° (SD 2.2) respectively in the age 80+ cohort versus -3.2° (SD 13.9) and 5.9° (SD 3.1) in the 60-69 year-olds.

Conclusion

Significant kinematic gait differences were observed between geriatric volunteers and controls. Age-related gait differences were found within the geriatric study population. These findings have clinical implications for understanding fall predisposition, directing rehabilitation, and guiding medical and surgical approaches to lessen the impact on gait changes. The study identifies significant declines in geriatric gait and serves as a useful reference for future studies in the geriatric population.

Level of Evidence

Prognostic Cohort Study, Level III

INTRODUCTION

The world population is aging, with the oldest population increasing at the greatest rate (Ambrose, Paul, and Hausdorff 2013; Murphy et al. 2008). Falls, arthritis, and sarcopenia are seen primarily in older individuals. Abnormal gait may not only predispose to these conditions, but also result from them. In addition, robust physical function and the ability to carry out activities of daily living are predictors of morbidity and mortality (Milte and Crotty 2014).

Analysis of gait in the elderly has focused primarily on gait speed, lower extremity strength, and measures of physical performance, such as the "Timed Get Up and Go" test (TGUG) (Scott et al. 2014). Studies utilizing these tools have found persistent significant declines in patients' gait following surgery for fragility fractures (Fredman et al. 2005; Lloyd et al. 2009; Magaziner et al. 2000). The etiology behind this disproportionate decline in gait following lower extremity fragility fractures, despite advancements in surgical technique and physical therapy, remains unclear. A greater understanding of the kinematic, kinetic, and spatiotemporal parameters of lower extremity motion will assist in establishing normative data for elderly gait and further the orthopaedic surgeon's ability to assess gait changes following fragility fractures.

The primary goal of this study is to describe, within the context of their overall health and physical function, gait parameters of elderly volunteers. Our secondary aims include investigating differences in gait parameters across age and exploring possible demographic and health-related associations with gait.

METHODS

This was a prospective, cross-sectional, observational study conducted at two hospitals from October 2013 to February

2015. Institutional review board approval was obtained and all study volunteers provided informed consent.

Twenty-five subjects, all 60 years old or older with no medical condition affecting their ability to ambulate or history of a prior fracture or lower extremity surgery, were recruited for the study. Subjects were excluded if they were unable to read or speak English, ambulated with an assistive device, or had a former or current condition that would affect their gait. Subjects with lower extremity osteoarthritis were included as long as they were not currently undergoing any active therapy for it. Subject recruitment was stratified into three age groups (60-69, 70-79, and 80+ years old) with a minimum requirement of seven subjects per group. This was done to ensure as large an age range as possible given the small sample size. All analyses were done on the cohort as a whole.

Standard gait analysis was conducted to collect physical exam, spatiotemporal, kinematic, and kinetic data of the volunteers' bilateral lower extremities. Physical exam measurements were used to assess the static range of motion of the hip, knee and ankle. Motion capture data were collected using a 12 camera Vicon T160 optical motion capture system (Vicon, Oxford, UK) and 6 AMTI OR6 force plates (AMTI Watertown, MA). Subjects walked barefoot across the room at a comfortable walking speed. They repeated this multiple times until three valid trials were collected. Motion capture data were processed using the Plug-in-Gait model with functional model calibration (Vicon, Oxford, UK).

Static range of motion data for hip, knee, and ankle were recorded as maximum bidirectional measures (degrees) by a single examiner. Differences in leg length were reported as an absolute value. Gait parameters of joint kinematics and joint kinetics (forces across the joint expressed in Nm/kg) were recorded as uni-directional measures from the minimum to maximum motion observed during the gait cycle. For ease of reporting, minimum measures were presented

using bidirectional descriptors (e.g. minimum knee flexion equates to knee extension, and so forth).

Following gait analysis, subjects completed five questionnaires and outcomes tools including: FRAX, WOMAC, SF-12, Rapid Assessment of Physical Activity (RAPA), and Fried Frailty Index. The Fried Frailty Index is a validated frailty assessment described by Fried et al. and incorporates strength assessment, calorie expenditure, and walking speed into its score (Bandeem-Roche et al. 2006; Fried et al. 2001). RAPA is a validated tool that assesses patient reported aerobic physical activity (RAPA 1) and strength and flexibility (RAPA 2) (Topolski et al. 2006). Demographic and study data were collected from patient medical records and used to complete the Charlson Comorbidity Index (CCI).

Univariate regressions were performed to estimate the relationship between subject characteristics and a 10-year greater age. Linear regressions were used for continuous variables; logistic regressions and odds ratios were used for binary variables; ordinal logistic regressions and odds ratios for a one-unit increase were used for ordinal variables. All analyses in this pilot study were exploratory. No p-values were adjusted for multiple comparisons.

Gait parameters, on both sides, were measured for each of the 25 patients. For each patient a single side was chosen randomly for use in all analyses. Although the full gait analysis assessed many parameters, a few were selected as representative of key differences. Because gait parameters had repeated measures for each patient, ANOVA was used to compute the standard deviation within and between patients. Univariate mixed regressions with repeated measures for each patient estimated the association of a 10-year greater age on each of the selected gait parameters.

Gait data from 83 pediatric patients (age range 4-17 years) with mature gait walking at a self-selected speed were previously obtained and used for comparison to gait data from our 25 geriatric volunteers (Schwartz, Rozumalski, and Trost 2008). The population means, standard deviations and sample sizes from this data were used to estimate the mean difference and its standard error. The 95% confidence intervals (CIs) and two-tailed p-values for differences in means were computed assuming normality.

For gait parameters significantly associated with age, we explored potential baseline predictors that may mediate the effect of age or contribute independently. The additional predictors were investigated one by one due to the small sample size. Each regression had two predictors: age (per 10 years) and the proposed additional variable. Data were modeled using a mixed model with repeated measures within patient and a compound symmetry correlation structure. Model fit was assessed using -2Log(Likelihood) . With the exception of the comparison of geriatric subjects and non-geriatric controls, all analyses were conducted in SAS 9.4.

RESULTS

DEMOGRAPHICS

The mean age for the 25 participants was 72 (SD 8). Forty-four percent were female and 20% were pre-frail. Mean CCI was 0.44 (0.71). Mean WOMAC pain, stiffness, and functionality were 0.52 (1.00), 1.28 (1.65), and 0.16 (0.47), respectively. The mean FRAX was 10.8 (8.7). RAPA1 and RAPA2 were 0.40 (0.50) and 0.88 (0.88), respectively. Patient demographic, health-related information, and static range of motion data are presented in [Table 1](#).

Subject characteristics were assessed for possible associations with a 10-year increase in age [Table 2](#). Older patients were shorter (5.1 cm; CI 1.0, 9.2), had a higher CCI (OR 3.43; CI 0.99, 11.85 for a one-unit higher score) and a higher FRAX (4.6; CI 0.5, 8.6), and had less ankle dorsiflexion (knee flexed) (4.2 degrees; CI 1.2, 7.2). Other differences were not significant. P-values were not adjusted for multiple comparisons.

GAIT ANALYSIS COMPARISON BETWEEN GERIATRIC AND NON-GERIATRIC CONTROL GROUPS

Twelve parameters had significant differences between the 25 geriatric subjects and 83 non-geriatric controls [Table 3](#), [Figure 1](#), [Figure 2](#). Geriatric volunteers had a mean of 8.3 (5.3, 11.3) degrees less ankle plantar flexion, but 2.8 (1.3, 4.3) degrees greater dorsiflexion during the gait cycle. The mean knee flexion and extension during stance phase in the geriatric cohort were 3.4 (0.9, 5.9) degrees and 5.2 (3.0, 7.4) degrees less, respectively. The geriatric cohort had 7.5 (1.6, 12.4) degrees less hip extension and 4.1 (0.0, 8.2) degrees greater hip flexion during the gait cycle, but this was only borderline significant. Hip adduction was observed to be 2.0 (0.3, 3.7) degrees less in the geriatric cohort during the gait cycle.

Three kinetic parameters (forces acting across the joint) were significantly different between the geriatric volunteers and the non-geriatric controls. The geriatric group had an increased knee extension moment of 0.13 (0.04, 0.20) Nm/kg and an increased knee flexion moment of 0.06 (0.00, 0.11) Nm/kg. There was also a significant increase of 0.19 (0.10, 0.28) Nm/kg in hip abduction moments when compared with the controls. The non-dimensional step length (Hof 1996) was 0.06 (0.02, 0.10) or 6% significantly less than the controls.

GAIT COMPARISON WITHIN THE GERIATRIC PATIENT GROUP SUBDIVIDED BY AGE

Within the geriatric group, five gait parameters were significantly associated with age. Ten years greater age was predictive of 2.70 (0.42, 4.97) degrees less knee extension and 7.03 (1.65, 12.4) degrees less hip extension [Table 4](#). Hip flexion moment was the only kinetic parameter with an age association; a decade greater age was associated with a 0.19 (0.06, 0.32) Nm/kg lower force. Both non-dimensional speed and non-dimensional step length were negatively associated with age at estimated 0.03 (0.00, 0.06) or 3% and

Table 1. Baseline Characteristics of the Geriatric Study

Characteristic	N (%) or Mean (Std Dev)
Age (years)	72 (8)
Female	11 (44%)
Height (cm)	172 (9)
Weight (kg)	80 (13)
BMI (kg/m ²)	27 (3)
Fried Frailty Index (No. of pre-frail)	5 (20%)
Charlson Comorbidity Index	0.44 (0.71)
WOMAC:	
Pain	0.52 (1.00)
Stiffness	1.28 (1.65)
Functionality	0.16 (0.47)
FRAX	10.8 (8.7)
RAPA1	0.40 (0.50)
RAPA2	0.88 (0.88)
SF-12 (quality of life):	
Physical	52 (8)
Mental	58 (4)
Leg Length Difference (cm)	0.36 (0.39)
Static Range of Motion Measures (degrees)	
Ankle Dorsiflexion – Knee Flexed	16.2 (6.7)
Ankle Dorsiflexion – Knee Extended	8.4 (3.1)
Ankle Plantar Flexion	41.8 (11.2)
Knee Flexion	126.8 (11.6)
Knee Extension	-1.0 (3.5)
Hip Flexion	118.2 (7.2)
Hip Extension	3.3 (8.3)
Hip Abduction	31.0 (5.8)
Hip Internal Rotation	42.0 (9.2)
Hip External Rotation	39.0 (7.5)

0.05 (0.01, 0.09) or 5% less per decade, respectively (Hof 1996).

All study subject characteristics other than static range of motion and leg length were explored as age-adjusted predictors of four selected gait parameters associated with age [Appendix]. Age-adjusted BMI, Fried Frailty Index, CCI, RAPA2, and the Mental scale for the SF12 were predictive of differences in knee extension during gait. Sex and RAPA2 were predictive of differences in hip extension during gait. BMI was the only subject characteristic predictive of decreasing non-dimensional speed. Finally, height was predictive of a change in hip flexion moment.

DISCUSSION

Lower extremity function declines with age and is associated with significant disability and morbidity (Alcock, O'Brien, and Vanicek 2015; Guralnik et al. 1994, 2000, 1995; Shumway-Cook et al. 2007). The importance of examining factors that influence gait and balance following fractures in geriatric patients has been noted (Carpenter and Stern

2010). Gait analysis has been used increasingly in the field of joint reconstruction and has provided objective outcome measures for assessing surgical approaches, rehabilitation, and multiple other variables in total joint arthroplasty (Sinha et al. 2011). Gait analysis is the next step in assessing outcomes in geriatric patients and designing more appropriate interventions for them. As the technology progresses, this data may help supplement video and telemetric data easily accessible via cell phone to help track declining function in real time. Data describing gait in healthy geriatric patients within the wider context of their health and demographic factors is limited. Our study fills this gap and examines variability in gait parameters among relatively healthy geriatric patients.

LIMITATIONS

This is an exploratory study; the descriptive results should be interpreted as hypothesis-generating and not conclusive. The exclusion of unhealthy geriatric patients and the small sample size make it difficult to generalize results to a

Table 2. Association of Baseline Characteristics with a 10-Year Greater Age.

Characteristic	Difference (95% CI) per 10-Year Greater Age*	Odds Ratio (95% CI) per 10-Year Greater Age*	p-value
Female		1.35 (0.48, 3.77)	0.57
Height (cm)	-5.1 (-9.2, -1.0)		0.02
Weight (kg)	-0.8 (-7.4, 5.8)		0.81
BMI (kg/m ²)	1.3 (-0.3, 2.9)		0.13
Fried Frailty Index (Pre-Frail or Frail)		3.82 (0.81, 18.01)	0.09
Charlson Comorbidity Index		3.43 (0.99, 11.85)	0.05
WOMAC:			
Pain		0.87 (0.29, 2.64)	0.81
Stiffness		2.56 (0.94, 6.97)	0.07
Functionality		0.82 (0.17, 3.95)	0.81
FRAX	4.6 (0.5, 8.6)		0.04
RAPA1		0.66 (0.23, 1.90)	0.44
RAPA2		0.59 (0.22, 1.55)	0.28
SF12 (quality of life):			
Physical	-2.7 (-6.7, 1.3)		0.20
Mental	0.8 (-1.3, 2.9)		0.47
Leg Length Difference (cm)	0.16 (-0.04, 0.36)		0.14
Static Range of Motion Measures (degrees)			
Ankle Dorsiflexion – Knee Flexed	-4.2 (-7.2, -1.2)		0.01
Ankle Dorsiflexion – Knee Extended	-1.5 (-3.0, -0.0)		0.06
Ankle Plantar Flexion	-1.9 (-7.6, 3.8)		0.51
Knee Flexion	-2.8 (-8.7, 3.0)		0.35
Knee Extension	0.5 (-1.3, 2.3)		0.61
Hip Flexion	-2.5 (-6.0, 1.1)		0.18
Hip Extension	-1.0 (-5.3, 3.2)		0.64
Hip Abduction	-2.5 (-5.3, 0.3)		0.10
Hip Internal Rotation	0.0 (-4.7, 4.8)		1.00
Hip External Rotation	0.0 (-3.8, 3.9)		0.99

*Continuous variables are listed as estimated differences per 10 years increase in age (slope), dichotomous and ordinal variables are listed as estimated odds ratios for a 10 year increase in age.

diverse geriatric population with large variations in health and physical ability. However, the variability of range of motion and gait measures was similar in the geriatric and non-geriatric groups, indicating that future studies will find the diversity in geriatric patients manageable. The choice of a relatively young comparison group should not affect the results as the gait pattern is known to mature by age 7, and non-dimensional parameters were used to negate changes due to growth (Sutherland 1997). This study focuses on the lower extremity. Upper extremity and spine motion cannot be assessed with this methodology although they are likely to change with age as well. Subjects' gait may have been influenced by the awareness that they were being observed. We tried to control for this by asking patients to walk through the gait lab multiple times and at a comfortable pace.

PRIMARY OBJECTIVE

The goal of our study was to describe gait parameters in a healthy geriatric group of volunteers within the context of their overall health and to utilize a non-geriatric control group for comparison. Our study population could be considered healthy based on their CCI, WOMAC, Frailty Index, SF-12, and RAPA scores. Still, our study reveals significant differences when compared with younger controls. In general, there is a decreasing arc of motion and a tendency to a flexed position in geriatric patients. Hip extension, knee extension, and ankle plantar flexion in particular held a greater than 5 degree difference between the two groups with an 8.3 degree loss of plantar flexion and a 7.5 degree loss of hip extension in the geriatric volunteers. These differences in geriatric gait may be the result of age-related declines in physiology and/or subsequent compensatory mechanisms, such as for balance and proprioception de-

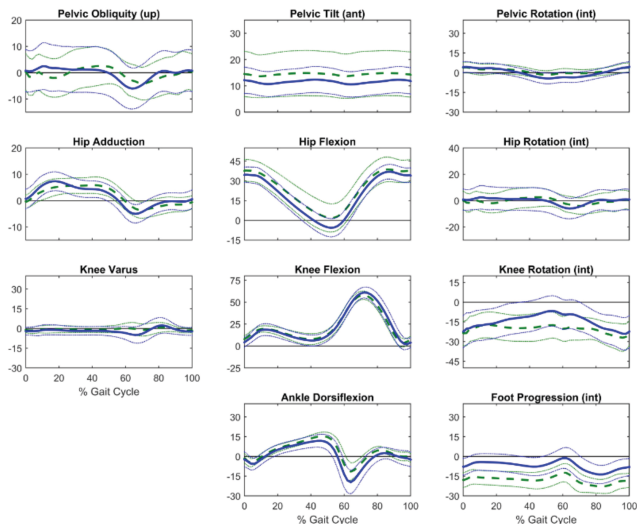


Figure 1. Comparison of kinematics between the geriatric (green, dashed lines) and control (blue, solid lines) groups.

The geriatric group has diminished ranges in the sagittal plane hip, knee, and ankle kinematics, as well as increased anterior pelvic tilt and increased external foot progression.

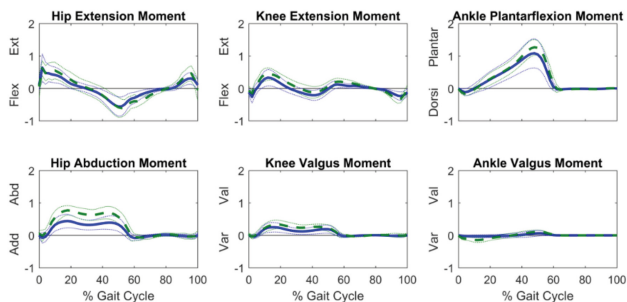


Figure 2. Comparison of kinetics between the geriatric (green, dashed lines) and control (blue, solid lines) groups.

The geriatric group has a larger knee extension moment and a larger hip abduction moment.

clines. Electromyography (EMG) studies have found increased co-activation of opposing muscle groups in elderly people during single support phase and late stance (Schmitz et al. 2009; Toda, Nagano, and Luo 2016). Co-activation of opposing muscle groups likely increases one's sense of stability and may explain some loss of motion seen in our study population. In addition, the geriatric volunteers' ankle dorsiflexion motion increased which may be a compensatory mechanism to prevent falls. Strengthening and range of motion exercises may play an even more important role following surgical intervention and gait rehabilitation to address these changes.

Muscle power deteriorates with age and is a sensitive assessment for sarcopenia (Lauretani et al. 2003). Quadriceps strength, in particular, has been reported to account for up to 86% of the variance in walking speed among elderly patients (Bassey et al. 1992). Although our study revealed some differences in lower extremity moments at maximum knee flexion, knee extension, and hip abduction between the geriatric and non-geriatric control groups, these differences are small and likely not clinically significant. Sarcopenia may explain some of the age-related declines in motion especially related to hip and knee extension, but its effect is likely limited in a healthy geriatric population.

Previous gait studies suggest mild osteoarthritis may lead to gait changes (Leigh, Osis, and Ferber 2016). Still, other reports have found osteoarthritis effects on gait to be closely tied to progression of patient symptoms (Ko et al. 2011). Given this, gait changes in older individuals are likely influenced to a degree by degenerative changes, but the magnitude may be reduced in asymptomatic individuals.

SECONDARY OBJECTIVE #1 DIFFERENCE IN GAIT PARAMETERS ACROSS AGE

The geriatric subjects demonstrated significant differences in gait parameters with increasing age. Hip extension, knee extension, gait speed, and hip flexion moments held a negative association with every decade increase in age. Hip extension, in particular, revealed a strong association with a 7.03 (1.65, 12.40) degree loss per decade. Our results support a study by Stenholm et al. reporting lower hip range of motion as a key predictor of mobility loss over 9 years (Stenholm et al. 2015). The loss of hip extension may be a key prognostic tool to assess geriatric mobility and safety. Gait speed has been well-reported to decline with age and is often theorized as a mechanism to compensate for increased energy expenditure of walking due to age and chronic conditions (Schrack et al. 2012). The etiology of the negative association between age and hip flexion moments is unclear but may be a mechanism of decreasing forces through the hip. Prior studies have found maximum hip flexion moment is reduced in patients with hip osteoarthritis, yet there is often a reduction in other gait parameter forces which was not seen in our study (Eitzen et al. 2012; Tateuchi et al. 2014).

SECONDARY OBJECTIVE #2 FACTORS INFLUENCING A DECLINE IN GAIT

Our last objective was to identify study subject characteristics that might be predictive of gait parameters even after adjustment for age. Previous studies have found gender, BMI, diabetes, recent infection, inflammatory conditions, and gait speed as prognostic factors of impending disability in community dwelling populations (Ko et al. 2011; Stenholm et al. 2015).

In our study, bivariate age-adjusted regressions revealed that only height was significantly predictive of maximum hip flexion moment, while several parameters were significantly predictive of hip extension moment. Only BMI and

Table 4. Gait Parameters and their association with age.

Gait Parameter	Mean	Standard Deviation	Increase Associated with a 10-Year Greater Age	p-value
Within Patient	Between Patients			
Kinematic Gait Parameters* (Degrees)				
Ankle Dorsiflexion	15.8	1.1	3.0	1.11 (-0.35, 2.56) 0.15
Ankle Plantar Flexion	13.3	2.1	5.8	-2.05 (-4.90, 0.80) 0.17
Knee Flexion	58.4	1.4	5.3	0.50 (-2.20, 3.20) 0.72
Knee Extension – Stance Phase	-7.5	0.9	4.9	-2.70 (-4.97, -0.42) 0.03
Hip Flexion	42.4	1.1	10.0	3.26 (-1.69, 8.21) 0.21
Hip Extension	-1.5	1.1	11.9	-7.03 (-12.40, -1.65) 0.02
Hip Adduction	5.9	0.8	3.9	0.57 (-1.51, 2.65) 0.59
Hip Abduction	6.0	0.7	4.1	-0.17 (-2.20, 1.86) 0.88
Maximum Foot Progression	-11.0	2.6	6.0	-2.40 (-5.40, 0.50) 0.12
Non-dimensional Gait Measures				
Gait Speed	0.4	0.0	0.1	-0.03 (-0.06, -0.00) 0.03
Step Length	0.7	0.0	0.1	-0.05 (-0.09, -0.01) 0.01
Kinetic Gait Parameters** (Nm/kg)				
Ankle Plantar Flexion Moment	1.1	0.4	0.3	0.01 (-0.16, 0.18) 0.88
Ankle Dorsiflexion Moment	0.1	0.0	0.1	-0.02 (-0.05, 0.00) 0.11
Knee Extension Moment	0.5	0.1	0.2	-0.07 (-0.14, 0.01) 0.09
Knee Flexion Moment	0.4	0.0	0.1	-0.04 (-0.10, 0.02) 0.20
Hip Extension Moment	0.7	0.1	0.2	-0.04 (-0.13, 0.06) 0.46
Hip Flexion Moment	0.7	0.1	0.3	-0.19 (-0.32, -0.06) 0.01
Hip Abduction Moment	0.7	0.2	0.2	0.08 (-0.02, 0.18) 0.13
Hip Adduction Moment	0.2	0.0	0.1	-0.03 (-0.06, 0.01) 0.12

*Arc of joint motion during gait cycle.

**Forces acting across the joint during gait cycle.

the CCI were significantly predictive of more than one gait parameter in age-adjusted bivariate regressions. Our data suggest that future studies of geriatric gait would benefit from taking into account frailty, activity level, comorbidities, BMI, and height.

CONCLUSION

Functional mobility is an essential to the overall health and well-being of the geriatric population. Gait analysis has been shown in previous studies to be a valuable tool for interventionists – particularly orthopaedic surgeons – seek-

ing to assess and improve patients' functional outcomes (Tateuchi et al. 2014). This study identifies a negative association with age between arcs of motion throughout the lower extremity and identifies potential additional demographic and health-related predictors of gait parameters. These data may support future research and the development of interventions designed to mitigate specific gait

deficits associated with increased age and fracture treatment.

Submitted: August 05, 2021 EDT, Accepted: October 17, 2021 EDT



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SUPPLEMENTARY MATERIALS

Table 3

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