USING KINETIC AND KINEMATIC PARAMETERS
TO EXPLAIN CHANGES IN GAIT
DUE TO COGNITIVE TASKS

by

Kelly M. Seymour

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

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ABSTRACT

Although historically considered an automatic process, gait control has been shown to consume attentional demands, supported by the concept of dual-tasking with a motor and cognitive challenge. Identifying the impact of cognitive challenges on motor tasks in healthy younger and older adults could detect increased fall risk and lead to prevention strategies for at risk populations, such as the elderly or cognitively impaired. The impact on kinetics, kinematics, and spatiotemporal variability due to dual-tasking is currently unknown. The objective of this study is to identify how dual-tasking impacts motor task performance in healthy younger and older adults.

Eleven healthy younger (20.1 ± 1.9 years) and eleven healthy older (60.5 ± 9.4 years) adults first completed a neuropsychological assessment consisting of various cognitive tests to define a baseline measure of cognitive abilities. Three tasks were repeated during treadmill walking: a working memory task (Paced Auditory Serial Addition Test, PASAT), a visual attention and processing speed task (Symbol Digit Modalities Test, SDMT), and a visual attention and fine motor skills task (cellular phone dialing task, Phone).

Three walking conditions were used for dual-tasking: self-selected, fast (120% of self-selected), and limp (induced by the instrumented split-belt treadmill with one belt moving at self-selected speed and one belt moving at fast speed). Kinetic, kinematic, and spatiotemporal parameters were recorded, and statistical analysis (ANOVA) was run separately for older and younger adults with cognitive test as the independent variable.

Under dual-task conditions, it was found that mean stride width increased for younger adults during the fast (p = 0.028) and self-selected (p = 0.034) walking conditions while performing the SDMT task compared to walking with no cognitive challenge. In addition, both younger and older adults displayed trends of decreasing stride length and increasing stride width with the addition of all three dual-tasks under all three walking conditions. Also, younger adults showed an increasing trend in stride length and width variability under all three walking conditions for the SDMT dual-task challenge. Finally, older adults showed a decreasing trend in hip and knee range of motion with the addition of all three dual-tasks at all three walking conditions.

Dual-tasking produced few significant results for both healthy younger and older adults. These results could be due to a number of factors. First of all, a number of parameters had a large effect size (>0.14), suggesting limited statistical power. This could be due to large standard deviations and/or a small sample size. In addition, under controlled speed conditions participants had to compensate for a situation in which they would normally slow their walking speed. Because walking speed and kinematic parameters are often confounded, keeping a constant walking speed may have also led to constant gait patterns under dual-task conditions. Furthermore, participants may have adopted a "posture-first" strategy in which the motor task was prioritized at the expense of the cognitive task. This would result in the normal gait patterns seen in this study during dual-tasking.

Dual-tasks may increase fall risk in older adults if the gait changes are indicative of a fall, such as decreased stride length, increased stride width, increased variability of stride length and width, or decreased hip or knee range of motion.

Although not statistically significant, these trends are displayed for both healthy younger and older adults in this study. Because healthy individuals trend toward these gait parameters while dual-tasking, it is probable that the elderly or cognitively impaired would show significant changes in these parameters while dual-tasking, which could put vulnerable populations at risk for a fall. Future implications include developing prevention strategies for older adults at risk of falls.

Chapter 1

INTRODUCTION

1.1 Dual-Tasking

The average American adult takes between 5,000 and 7,000 steps per day, or on the order of millions of steps per year [Parker-Pope, 2010]. Despite the degree of practice and experience with gait control, studies have shown that gait is not a fully automatic task and consumes attentional resources within the brain [Abernethy et al., 2002]. Attention is defined as the information processing capacity of an individual, with the theory that cognitive and motor tasks both consume attention, leading to the deterioration in performance in one or both tasks when performed simultaneously [Woollacott et al., 2002].

This idea has largely been proven with the concept of dual-tasking, which serves to reveal the interactions between cognitive processing and motor behavior by challenging participants to simultaneously perform motor and cognitive tasks [Plummer-D'Amato et al., 2008]. In theory, if the dual-task is sufficiently challenging, the performance on the motor task will be impacted due to the addition of a cognitive task when compared to performing a motor task alone in one of two ways. Participants may perform with a "posture first" strategy, where the motor task is prioritized at the expense of the cognitive task performance, or they may prioritize the cognitive task and have the motor task performance suffer, possibly leading to decreased stability or even a fall [Bootsma-van der Wiel et al., 2003].

Understanding the relationship between cognitive and motor task performance during dual-tasking has become a prominent field of research in recent years as a result of the possible implications for cognitive and motor recovery after a stroke or other neurological injury [Plummer-D'Amato et al., 2008]. In addition, the increasing older adult population, defined as individuals over the age of 65, has received heightened attention in the health care system in terms of health conditions, disability, and mental health [Gobbo et al., 2014]. It has been estimated by the United Nations that by the year 2050, one-tenth of the global population will be individuals over the age of 65 with adults over 80 being the fastest growing population division [Gobbo et al., 2014]. Therefore, fall risk and prevention as well as understanding the link between cognitive and motor processing has become increasingly important. Fields ranging from biomechanics and psychology to brain mapping and kinesiology are investigating the effect of gait on cognition, or like this study, the effect of cognition on gait [Yogev-Seligmann et al., 2008].

Mixed findings have been reported in the literature as to what specific types of cognitive tasks impact gait. Some studies have observed working memory tasks, defined as the part of short term memory involving monitoring incoming information to update and replace old information with new relevant information for the desired task [Liu-Ambrose et al., 2009]. Montero-Odasso et al. showed that a working memory task led to a reduced gait speed and a decreased working memory performance, whereas Plummer-D'Amato et al. found that working memory tasks produced the smallest reduction in gait speed when compared to other types of dual-tasks such as visuospatial cognition and verbal fluency [Montero-Odasso et al., 2009; Plummer-D'Amato et al., 2008].

In addition, conflicting reports have also been found with visual attention tasks, defined as tasks involving the examination of a visual scene and then using attention to properly process information as determined by the specific task [Poldrack et al., 2011]. Sparrow et al. reported that visual attention tasks increase reaction time, especially within the elderly population, and Yang et al. found that visual attention tasks had no significant effect on stride duration or cognitive task performance [Sparrow et al., 2002; Yang et al., 2006].

1.2 Younger Adults and Dual-Tasking

Although historically considered an automatic process, gait control has been shown to consume attentional demands, shown by a decreased performance in cognitive tasks and altered gait patterns while dual-tasking [Abernethy et al., 2002]. In younger adulthood, it is thought that gait is a relatively automatic process, suggesting that they have additional attentional resources available to handle difficult cognitive and motor tasks during dual-tasking [Lövdén et al., 2008]. But studies have shown that dual-tasking even impacts the gait of young adults, shown by increased spatiotemporal variability and decreased gait speed and cognitive performance, indicating that gait is not a purely motor task but also involves cognition and attention [Srygley et al., 2009; Yogev-Seligmann et al., 2008]. In addition, the number of pedestrian deaths has increased 7% from 2009 to 2011 with an additional 69,000 pedestrian injuries [Daily Mail, 2013]. Real world pedestrian dual-task distractions, such as texting and walking, have been implicated with this increase, indicating that dual-task walking even impacts younger adults.

The impact on kinetics, kinematics, and spatiotemporal variability due to dual-task distractions is currently unknown for younger adults. So, studying kinetic and

kinematic parameters as well as spatiotemporal variability will reveal the impact on gait during dual-tasking in younger adults. In healthy young adults, the effects of dual-tasking should be revealed especially in spatiotemporal gait parameters across all types of dual-tasking. Stride width and stride width variability relates to balance control while stride length and stride length variability relates to the motor control of rhythmic gait patterning, both processes that are expected to be impacted in the gait of younger adults during dual-tasking [Lövdén et al., 2008]. With the moderate cognitive challenges provided in this study during dual-task conditions, the kinetics and kinematics of younger adults are expected to remain fairly constant across all dual-task conditions.

Understanding the effect of dual-tasking in young adults may also allow for inferences to be made about the impact of dual-tasking in the elderly or those with various cognitive impairments because gait requires more attention in these "at-risk" populations. The effects of dual-tasking in young adults will also show whether cognitive tasks are prioritized over motor tasks, or vice versa.

1.3 Older Adults and Dual-Tasking

Approximately 25% of all 70 year olds fall at least once per year, increasing to 35% of 75 year olds and 50% of those over 80 [Bock, 2008]. While there are many factors that may cause a fall, over 50% of falls in the elderly population occur while walking or during another form of locomotion [Barak et al., 2006; Hausdorff et al., 2001]. In addition, most falls do not occur during walking alone, but rather while dual-tasking between walking and some cognitive task, such as holding a conversation or making a mental grocery list [Bootsma-van der Wiel et al., 2003; Bridenbaugh et al., 2011; Priest et al., 2008; Woollacott et al., 2002]. Even if the fall does not result in a

physical injury, the psychological effects of falling such as increased fear of falling, increased inactivity, or increased dependence on others often result in nursing home placement, hospitalization, or functional disability [Bock, 2008; Brach et al., 2001; Hausdorff et al., 2001]. Both gait and cognitive impairments, which are common and often coincide in older adults, may have a large impact on quality of life and everyday functioning for older adults [Van Iersel et al., 2008]. In addition, fall accidents are the number one cause of unintentional injury and hospitalization in individuals over the age of 65 and are second only to motor vehicle accidents in leading causes of death under accidental circumstances world-wide [Bridenbaugh et al., 2011; Lockhart et al., 2003].

Early detection of gait or cognitive disorders in older adults is crucial, allowing for early intervention and fall prevention [Bridenbaugh et al., 2011]. It has been previously proven that a decreased stride length, increased stride width, increased stride length and width variability, and decreased hip and knee range of motion are factors indicative of a fall in older adulthood [VanSwearingen et al., 1996; Wolfson et al., 1990]. Identifying changes in gait such as those aforementioned while performing cognitive tasks could lead to reducing the risk of falling for many individuals and possible rehabilitation strategies for those who have fallen or are predicted as at-risk fallers [Bridenbaugh et al., 2011; Priest et al., 2008]. It is currently unclear what types of dual-tasking events, including motor and/or cognitive challenges, lead to kinematic, kinetic, or spatiotemporal gait changes and therefore decreased balance and stability.

In older adulthood, the impacts of dual-tasking are expected to align with the changes of gait parameters indicative of a fall. Because the maintenance and balance of gait in older adulthood is critical, dual-tasking is expected to highlight these

changes in gait. In addition, the cognitive tasks involving visual attention are expected to result in more changes in gait. In older adults, locomotion and stability during gait is specifically related to visual attention cognitive demands, with the effect increasing with age. Therefore, attention may be further divided during visual attention tasks, resulting in more gait changes than other types of cognitive dual-task challenges [Bock, 2008].

1.4 Dual-Tasking with Controlled Speed

In this study performed on an instrumented split-belt treadmill, controlling for speed while dual-tasking will allow us to see what gait parameters are altered, which could show the types of motor and cognitive tasks that are challenge enough to affect gait. Adding the treadmill component to this dual-tasking study will not significantly alter gait parameters compared to the typical over-ground studies. Barak et al. demonstrated that the biomechanics of over-ground and treadmill walking are similar, and no significant changes are made to gait parameters if the treadmill is held at a constant speed [Barak et al., 2006].

To our knowledge, very few studies have tested for the effects of dual-tasking while controlling gait speed. Previous studies have noted healthy young and older adults slow their gait speed during dual-tasking, but there is no consensus as to which type of dual-task causes this change [Bock et al., 2008; Priest et al., 2008; Srygley et al., 2009; Van Iersel et al., 2008]. For example, studies have reported dual-tasks with a working memory cognitive task result in reduced gait speed and poor working memory performance [Montero-Odasso et al., 2009]; conversely, working memory tasks also produce the smallest reduction in gait speed when compared to other types of dual-tasks such as verbal fluency [Plummer-D'Amato et al., 2008]. Mixed findings

have also been reported on the effect of a verbal fluency dual-task on gait speed in that when verbal fluency performance declines, gait speed is reduced [Bootsma-Van Der Weil et al., 2003], but also that verbal fluency tasks have no effect on gait speed in older people [Reelick et al., 2009].

In addition, in over-ground studies where participants control gait speed, kinetic, kinematic, and spatiotemporal parameters are impacted by a slower gait speed and therefore are confounded variables. By controlling gait speed on a treadmill, the effect of speed will be removed. As a result, controlling for gait speed in this study may highlight other changes in gait parameters in response to different types of dual-tasking.

1.5 Kinematics, Kinetics, and Spatiotemporal Parameters

This study is unique because it observes the effect of dual-tasking on gait not just through cognitive test performance or on spatiotemporal parameters, but also on kinematics and kinetics.

To our knowledge, no dual-tasking study has observed kinetic data in healthy younger or older adults and may prove useful to identify changes in gait. The instrumented split-belt treadmill allows for the collection of forces in three dimensions during gait. In this study, peak vertical ground reaction force was observed, defined as the reaction force applied by the ground to the foot in the vertical direction during gait [Perry, 1992]. If cognitive tasks lead to an increase or decrease in maximum vertical ground reaction force, it could be an indicator of stumbling due to abnormal loading or an altered gait pattern.

Lockhart et al. found that a high Required Coefficient of Friction (RCOF), defined as the ratio of the horizontal ground reaction force and the vertical ground

reaction force, was a risk factor for slip-induced falls [Lockhart et al., 2003; Lockhart et al., 2009]. This ratio has been used to identify when in the gait cycle a slip is most likely to occur, and has been found to be the vertical ground reaction force peak just after heel strike. In addition, the magnitude of the horizontal ground reaction force is affected by walking speed, a factor controlled in this study [Lockhart et al., 2003; Lockhart et al., 2009]. Therefore, identifying changes in peak vertical ground reaction force can indicate potential risk for slip-induced falls.

Spatiotemporal variability has been widely shown as a factor for fall risk and altered gait patterns [Brach et al., 2001; Bridenbaugh et al., 2011; Hausdorff et al., 2001; VanSwearingen et al., 1996]. Variability of stride width specifically has been associated with falls for older adults, and stride width is significantly influenced by the addition of a dual-task during walking [Alexander et al., 2008; Lövdén et al., 2008; Owings et al., 2004; Priest et al., 2008]. Studies have also shown significant findings for stride width variability during dual-tasking for younger adults, and that stride width variability in older adults is significantly higher than younger adults [Grabiner et al., 2005; Lövdén et al., 2008; Owings et al., 2004].

Analyzing spatiotemporal variability will detect altered gait patterns and possibly potential fall risk during dual-tasking in older and younger adults. This study observed the means and variability of stride length, defined as the distance between heel strikes of the same foot, and also stride width, defined as the perpendicular distance between heel strikes of both feet in the medio-lateral direction (Figure 1.1) [Perry, 1992]. Because this study was performed on an instrumented split-belt treadmill, instructions were given to keep one foot on each belt. As a result, stride

width may be larger than over-ground walking for subjects unfamiliar with split-belt walking [Zeni et al., 2011].

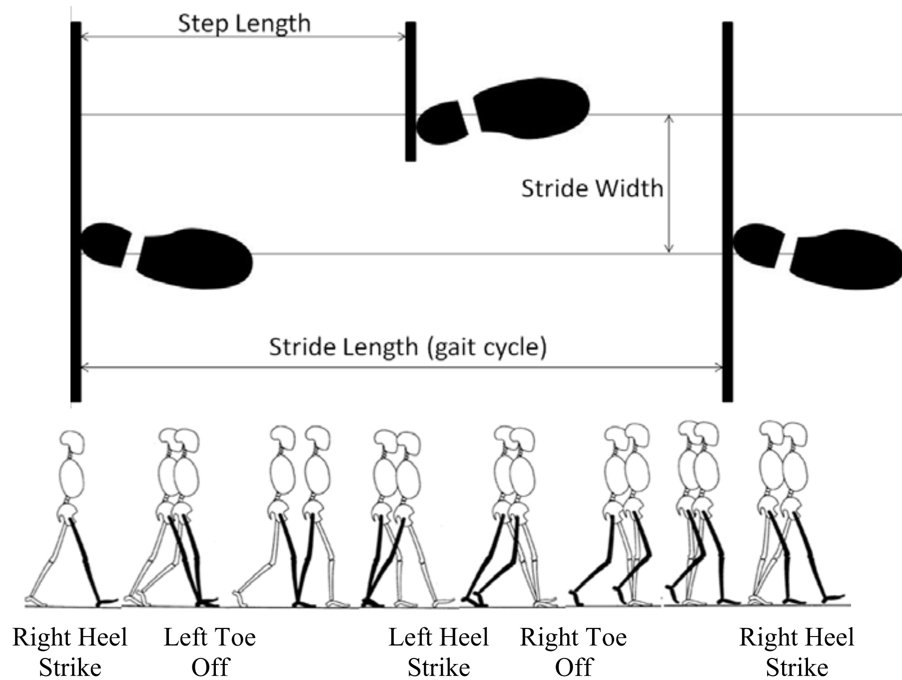

Figure 1.1: Spatiotemporal gait parameters. (Heel strike and toe off image adapted from Perry, 1992)

Previous studies have reported changes in gait parameters such as stride length, step width variability, cadence, and stride time with dual-tasking. It has been reported that older adults show an increase in stride time variability, stride length, and cadence while under dual-task conditions [Bridenbaugh et al., 2011; Lövdén et al., 2008; Plummer-D'Amato et al., 2008; Van Iersel et al., 2008]. However, to our knowledge, no other study has reported variations in kinematic parameters during dual-tasking.

Kinematic parameters have also been identified as contributing factors to falls in the elderly population, such as peak angles and range of motion for knee flexion, hip extension, and ankle plantarflexion [Barak et al., 2006; VanSwearingen et al., 1996; Wolfson et al., 1990]. Changes in kinematic parameters may depend on the type of dual-task challenge and/or the degree of motor task challenge.

This study observed peak angle values for hip extension during stance, hip flexion during swing, knee flexion during stance and swing, and ankle dorsiflexion and plantarflexion. In addition, the range of motion, or excursion from maximum to minimum angles, and variability at the hip, knee, and ankle were also analyzed.

1.6 Objective and Specific Aims

There is currently a limited understanding of the impact on kinetics, kinematics, and spatiotemporal parameters due to specific types of dual-tasking for both healthy younger and older adults while under controlled speed conditions. Therefore, the objective of this study was to identify the trade-off between motor and cognitive tasks in order to observe how dual-tasking affects walking in younger and older adults. This was accomplished by utilizing experimental gait analysis of younger and older adults during tests for various aspects of cognition to detect changes in spatiotemporal, kinematic, and kinetic parameters. The following specific aims will be addressed:

1. **Determine the effect of dual-tasking on kinetics, kinematics, and spatiotemporal parameters in healthy younger adults.** The kinetic and kinematic parameters of younger adults will be impacted similarly across all dual-task conditions, indicating a prioritization of the cognitive tasks over the motor tasks.

2. **Determine the effect of dual-tasking on kinetics, kinematics, and spatiotemporal parameters in healthy older adults.** Older adults will show limited changes in kinetics and kinematics with most dual-task conditions, however, a task that combines components of visual attention and memory will be the greatest dual-task challenge.

REFERENCES

Abernethy, B., Hanna, A., Plooy, A., 2002. The Attentional Demands of Preferred and Non-Preferred Gait Patterns. Gait & Posture 15, 256–265.

Alexander, N.B., Hausdorff, J.M., 2008. Guest Editorial: Linking Thinking, Walking, and Falling. The Journals of Gerontology. 63, 1325–1328.

Barak, Y., Wagenaar, R.C., Holt, K.G., 2006. Gait Characteristics of Elderly People with a History of Falls: A Dynamic Approach. Physical Therapy 86, 1501–1510.

Bock, O., 2008. Dual-Task Costs While Walking Increase in Old Age for Some, but Not for Other Tasks: An Experimental Study of Healthy Young and Elderly Persons. Journal of Neuroengineering and Rehabilitation 5, 27.

Bock, O., Engelhard, K., Guardiera, P., Allmer, H., Kleinert, J., 2008. Gerontechnology and Human Cognition: Impact of Cognitive Decay on the Ability to Operate Remote-Controlled Devices While Walking. IEEE Engineering in Medicine and Biology 27, 23–28.

Bootsma-van der Wiel, A., Gussekloo, J., de Craen, A.J.M., van Exel, E., Bloem, B.R., Westendorp, R.G.J., 2003. Walking and Talking as Predictors of Falls in the General Population: The Leiden 85-Plus Study. Journal of the American Geriatrics Society 51, 1466–1471.

Brach, J.S., Berthold, R., Craik, R., VanSwearingen, J.M., Newman, A.B., 2001. Gait Variability in Community-Dwelling Older Adults. Journal of the American Geriatrics Society 49, 1646–1650.

Bridenbaugh, S.A., Kressig, R.W., 2011. Laboratory Review: The Role of Gait Analysis in Seniors' Mobility and Fall Prevention. Gerontology 57, 256–264.

Daily Mail Reporter, 2013. Texting and Walking Blamed for the Nation-Wide Increase of Pedestrian Deaths. Daily Mail.

Gobbo, S., Bergamin, M., Sieverdes, J.C., Ermolao, A., Zaccaria, M., 2014. Effects of Exercise on Dual-Task Ability and Balance in Older Adults: A Systematic Review. Archives of Gerontology and Geriatrics 58, 177-187.

Grabiner, M.D., Troy, K.L., 2005. Attention Demanding Tasks During Treadmill Walking Reduce Step Width Variability in Young Adults. NeuroEngineering and Rehabilitation 2, 25.

Hausdorff, J.M., Rios, D.A., Edelberg, H.K., 2001. Gait Variability and Fall Risk in Community-Living Older Adults: A 1-Year Prospective Study. Archives of Physical Medicine and Rehabilitation 82, 1050–1056.

Liu-Ambrose, T, Katarynych, L.A., Ashe, M.C., Nagamatsu, L.S., Hsu, C.L., 2009. Dual-Task Gait Performance among Community-Dwelling Senior Women: The Role of Balance Confidence and Executive Functions. Gerontology 64, 975–982.

Lockhart, T.E., Woldstad, J.C., Smith, J.L., 2003. Effects of Age-Related Gait Changes on the Biomechanics of Slips and Falls. Ergonomics 46, 1136–1160.

Lockhart, T., Kim, S., Kapur, R., Jarrott, S., 2009. Evaluation of Gait Characteristics and Ground Reaction Forces in Cognitively Declined Older Adults With an Emphasis on Slip-Induced Falls. Assistive Technology : the Official Journal of RESNA 21, 188–195.

Lövdén, M., Schaefer, S., Pohlmeyer, A.E., Lindenberger, U., 2008. Walking Variability and Working-Memory Load in Aging: A Dual-Process Account Relating Cognitive Control to Motor Control Performance. Gerontology 63, 121–128.

Montero-Odasso, M., Bergman, H., Phillips, N.A., Wong, C.H., Sourial, N., Chertkow, H.,2009. Dual-Tasking and Gait in People with Mild Cognitive Impairment. The Effect of Working Memory. BMC Geriatrics 9, 41.

Owings, T.M., Grabiner, M.D., 2004. Variability of Step Kinematics in Young and Older Adults. Gait & Posture 20, 26–29.

Parker-Pope, T., 2010. The Pedometer Test: Americans Take Fewer Steps. New York Times.

Perry, J., 1992. Gait Analysis: Normal and Pathological Function. SLACK Incorporated: Thorofare, NJ.

Plummer-D’Amato, P., Altmann, L.J.P., Saracino, D., Fox, E., Behrman, A.L., Marsiske, M., 2008. Interactions between Cognitive Tasks and Gait after Stroke: A Dual Task Study. Gait & Posture 27, 683–688.

Poldrack, R.A., Kittur, A., Kalar, D., Miller, E., Seppa, C., Gil, Y., Parker, D.S., Sabb, F.W., Bilder, R.M., 2011. The Cognitive Atlas. www.cognitiveatlas.org.

Priest, A.W., Salamon, K.B., Hollman, J.H., 2008. Age-Related Differences in Dual Task Walking: A Cross Sectional Study. *J*ournal of Neuroengineering and Rehabilitation 5, 29.

Reelick, M.F., Van Iersel, M.B., Kessels, R.P.C., Olde Rikkert, M.G.M., (2009). The Influence of Fear of Falling on Gait and Balance in Older People. *A*ge and Ageing 38, 435–440.

Sparrow, W.A., Bradshaw, E.J., Lamoureux, E., Tirosh, O., 2002. Ageing Effects on the Attention Demands of Walking. Human Movement Science 21, 961-972.

Srygley, J.M., Mirelman, A., Herman, T., Giladi, N., Hausdorff, J.M., 2009. When Does Walking Alter Thinking? Age and Task Associated Findings. Brain Research 1253, 92–99.

Van Iersel, M.B., Kessels, R.P.C., Bloem, B.R., Verbeek, A.L.M., Olde Rikkert, M.G.M., 2008. Executive Functions Are Associated with Gait and Balance in Community-Living Elderly People. Gerontology 63, 1344–1349.

VanSwearingen, J.M., Paschal, K.A., Bonino, P., Yang, J.F., 1996. The Modified Gait Abnormality Rating Scale for Recognizing the Risk of Recurrent Falls in Community-dwelling Elderly Adults. Physical Therapy 76, 994–1002.

Wolfson, L., Whipple, R., Amerman, P., Tobin, J.N., 1990. Gait Assessment in the Elderly: a Gait Abnormality Rating Scale and Its Relation to Falls. Gerontology 45, M12–19.

Woollacott, M., Shumway-Cook, A., 2002. Attention and the Control of Posture and Gait: A Review of an Emerging Area of Research. Gait & Posture 16, 1–14.

Yang, Y.R., Chen, Y.C., Lee, C.S., Cheng, S.J., Wang, R.Y., 2006. Dual-Task-Related Gait Changes in Individuals with Stroke. Gait and Posture 25, 185-190.

Yogev-Seligmann, G., Hausdorff, J.M., Giladi, N., 2008. The Role of Executive Function and Attention in Gait. Movement Disorders 23, 329–342.

Zeni, J.A., Higginson, J.S., 2010. Gait Parameters and Stride-to-Stride Variability During Familiarization to Walking on a Split-Belt Treadmill. Clinical Biomechanics 25, 383-386.

Chapter 2

RESEARCH DESIGN AND METHODS

2.1 Participants

Eleven healthy younger adults and eleven healthy older adults completed psychological and gait analysis testing with three walking conditions (self-selected walking speed, fast walking speed, and with an induced limp serving as an alternate gait pattern) paired with various cognitive challenges. Subject information such as age, gender, and walking speed can be found in Table 2.1. Before beginning psychological and gait analysis, each subject provided written informed consent for participation in this study (Appendix A). This study was approved by the Institutional Review Boards on Human Subjects Research of the University of Delaware and the Loyola University of Maryland (Appendix D).

Table 2.1: Subject information for the eleven younger and eleven older adults who have completed psychological and gait analysis testing. Side of limp was determined randomly with a coin toss.

	Younger Adults Mean±SD (n=11)	**Older Adults Mean±SD (n=11)**
Age (years)	20.1 ± 1.9	60.5 ± 9.4
Gender (% male)	36.36	27.27
BMI	25.70 ± 5.1	23.86 ± 3.1
Self-Selected Speed (m/s)	1.11 ± 0.2	1.05 ± 0.2
Fast Speed (m/s)	1.33 ± 0.2	1.26 ± 0.3
Limp (% right)	73	45

2.2 Inclusion and Exclusion Criteria

Healthy younger and older adults were recruited using convenience sampling of individuals in the surrounding community of the University of Delaware. For this study, younger participants were between 18 and 23 years of age and older participants were over the age of 50. Because this study involves both gait and cognitive testing of healthy individuals, participants were excluded with anything that could affect their ability to perform in the gait analysis session and/or the cognitive measures session. Participants were issued a questionnaire either through a phone screening prior to testing or before beginning testing to ensure eligibility. The questionnaire of inclusion and exclusion criteria for this study can be found in Appendix B.

Subjects were excluded if they had any history of cardiac problems or illness such as heart murmur, chest pains, dizzy spells, rapid or irregular heartbeat, uncontrolled high blood pressure or high cholesterol, a family history of heart disease in parents or siblings prior to the age of 55, or diabetes. Subjects were also excluded with any problems affecting the brain, such as stroke, ADHD, depression, other psychological illness, or traumatic head injury resulting in lost consciousness for more than ten minutes. Finally, subjects were also excluded with problems possibly affecting gait, such as any muscle or bone injury, pregnancy, a BMI over 40, or other previous injury or pain (Appendix B).

2.3 Cognitive Measures

After providing informed consent, participants completed a one-on-one session consisting of various cognitive tests in order to define a baseline measure of cognitive abilities. All tests were issued by a trained student clinician under the supervision of a

licensed psychologist and performed while seated in a low stress environment in a small conference room on the University of Delaware campus. The cognitive measures performed included: Spatial Span, Shipley Measure of Abstraction, a cellular phone dialing task, Petride Self-Ordered Objects, Delis-Kaplan Executive Function System (verbal fluency, design fluency, Stroop test), Paced Auditory Serial Addition Test, WAIS 3rd Edition (picture completion, block design), Symbol Digit Modalities Test, Geriatric Depression Scale, and Activities of Specific Balance Confidence. These cognitive measures have been designed to test for various aspects of cognition, such as working memory, processing capacity, spatial perception, response inhibition, verbal fluency, visual attention, and problem solving [Poldrack et al., 2011]. In addition, the Geriatric Depression Scale and the Activities of Specific Balance Confidence served as self-reports to gauge level of depression and confidence during activities of daily living.

Three cognitive measures were repeated from the cognitive one-on-one session in the gait analysis session, requiring participants to walk on the treadmill at each of the three required walking conditions while performing specific cognitive tasks. In addition to walking at all three walking conditions without an issued cognitive task (No Test/Baseline), participants were asked to perform the Paced Auditory Serial Addition Task (PASAT), the Symbol Digit Modalities Test (SDMT), and the cellular phone dialing task (Phone) during both the gait analysis and one-on-one cognitive measures sessions.

	Baseline	PASAT	Phone	SDMT
Self-Selected				
Fast		(12 Trials presented in randomized order)		
Limp				

Figure 2.1: Schematic displaying the three required walking conditions and four cognitive challenges that make up the twelve walking trials for this study.

The PASAT is a classic working memory task in which 60 single digit numbers (1-9) are presented at a rate of every two seconds over a 120 second period through a standardized audio recording [Diehr et al., 1998]. Participants are asked to add two numbers at a time by adding the most recent number presented to the previous number stated in the recording. Participants are asked not to give a running total. This test requires auditory information processing speed through listening to the numbers and then computing a total. Memory is also a component of this test through remembering the previous number for addition [Diehr et al., 1998].

Another test administered while seated and then repeated during treadmill walking was the SDMT. In this task, participants are given an 8.5” x 11” sheet of paper with a code printed at the top where a symbol corresponds to one of nine digits, followed by a list of 110 symbols from the code printed in random order on the rest of

the page. Participants are given 120 seconds to verbally provide the numbers which correspond to as many symbols as they are able to complete by referencing the code printed at the top of the page [Lezak, 2004]. The SDMT is a processing speed and a visual attention task through how efficiently participants can match symbols from the code. There is also a slight component of memory because as the test goes on, participants may begin to memorize parts of the code and utilize this rather than their visual attention capabilities. The SDMT is also designed to test for reaction time and accuracy by how quickly and accurately they are able to reference the code and provide the corresponding numbers [Lezak, 2004].

The final test participants were asked to repeat from the seated condition to the walking condition was the Phone task, created specifically for this project. The Phone task is an ecological validity task, as it is a measure of something found in real life and is representative of actual functioning. Participants are visually presented with a ten digit phone number and asked to dial on a standard flip phone (Motorola Razor). A new ten digit number is visually presented after completion of dialing each set of numbers. Speed and accuracy of dialing over 120 seconds is assessed. This task is a nonverbal task with components of visual attention from looking at the number to then dial, and fine motor skills through the actual act of dialing.

Four different versions of each of these tasks were presented to each participant, once while seated, followed by one for each of the three walking conditions. Responses were recorded and then scored by a trained student clinician under the supervision of a licensed psychologist for each task. The different versions worked to minimize practice effects while keeping the same level of difficulty throughout each task.

2.4 Gait Analysis Session

To begin the gait analysis session, self-selected walking speed was measured using a ten meter over-ground walking trial. Participants were instructed to walk at a normal and comfortable pace, "as if strolling through a park or a grocery store." The middle six meters was timed with a stop watch, allowing for acceleration and deceleration for two meters on either end of the walking trial. Participants performed this over-ground walking trial twice, and the average velocity was computed and used as the self-selected speed for walking on the treadmill. In addition to the self-selected walking speed, participants were asked to perform two additional walking conditions on the treadmill: fast speed and with an induced limp. The fast walking speed was calculated as 120% of the self-selected speed, and the limp was created by moving one belt of the instrumented split-belt treadmill at each of the aforementioned speeds. The side of the limp was determined randomly with a coin toss.

Before beginning walking trials, all participants were fastened to a safety harness attached across the chest to the top of the treadmill with no body weight support. Participants walked at each speed under the following conditions: No Test (Baseline), PASAT, SDMT, and Phone. As shown in Table 2.2, there was one static standing calibration trial followed by twelve walking trials each two minutes long. The walking trials were presented in a randomized order determined by a random number generator for each participant in order to arbitrarily assign the order of cognitive tests and walking conditions, minimizing practice effects for both the motor and cognitive components. Instructions were given before beginning walking trials to avoid using the handrails attached to the treadmill, except in an emergency situation. Participants were given breaks whenever requested, or (on the rare occasions) when attached reflective markers for motion capture fell off. Total break times between trials were

recorded for each participant to ensure the effects of fatigue were not a factor between subjects. In total, the gait analysis session lasted approximately one hour.

Table 2.2: List of the twelve walking trials for the three walking conditions and four cognitive measures. Conditions #2-13 were presented in randomized order using a random number generator.

Condition #	Condition	Duration
1	Static Standing Calibration	10 sec
2	Self-Selected / Baseline	120 sec
3	Fast / Baseline	120 sec
4	Limp / Baseline	120 sec
5	Self-Selected / SDMT	120 sec
6	Fast / SDMT	120 sec
7	Limp / SDMT	120 sec
8	Self-Selected / PASAT	120 sec
9	Fast / PASAT	120 sec
10	Limp / PASAT	120 sec
11	Self-Selected / Phone	120 sec
12	Fast / Phone	120 sec
13	Limp / Phone	120 sec

The gait analysis session was performed on an instrumented split-belt treadmill (Bertec Corp., Columbus, OH) recording three dimensional forces with two embedded force plates capturing at 1080 Hz. In addition, kinematic data was recorded using Cortex with a 62 static marker set and 48 dynamic marker set with markers placed on anatomical landmarks over the legs, trunk, neck, and arms. A schematic of marker placements can be found in Appendix C. An eight camera passive motion capture system capturing motion of the reflective markers at 60 Hz was utilized (Motion

Analysis Corp., Santa Rosa, CA). Data processing was completed using Cortex and Visual 3D (C-Motion Inc., Bethesda, MD) using all gait cycles throughout each two minute trial (>100 gait cycles). Kinematic data was filtered using a bi-directional Butterworth low-pass filter at 6 Hz.

Peak knee flexion during stance and swing, hip flexion during swing and extension during stance, ankle plantar and dorsiflexion, and vertical ground reaction force (normalized to body weight) were determined and compared between conditions. In addition, stride length and width means and variability were analyzed to observe spatiotemporal changes. Finally, hip, knee, and ankle range of motion, in this study defined as excursion during gait, and standard deviations were analyzed for each participant for each condition.

2.5 Statistical Analysis

An a priori power analysis was conducted using G*Power to determine the proper sample size, which revealed that ten older adults and fourteen younger adults were required for appropriate power (University Düsseldorf, Düsseldorf, Germany). In order to balance the sample sizes, we tested a sample of eleven younger and eleven older adults. After data was collected, all variables were first summarized and reported as mean ± standard deviation (SD). An analysis of variance (ANOVA) was performed using JMP statistical software, version 11.0 (SAS, Cary, NC) to compare outcomes for each variable for each cognitive task (Baseline, PASAT, SDMT, and Phone) at each of the required walking conditions (self-selected, fast, and limp). Post hoc adjustments were performed using a Tukey's Test in order to reveal which cognitive measure resulted in a significant difference from the Baseline condition for each of the outcome variables. Significance level was defined at a p-value < 0.05. All analyses include the

right leg for each participant at the self-selected and fast speeds, and the leg at the fast speed for the limp walking condition.

REFERENCES

Diehr, M.C., Heaton, R.K., Miller, W., Grant, I., 1998. The Paced Auditory Serial Addition Task (PASAT): Norms for Age, Education, and Ethnicity. Psychological Assessment 5, 375-387.

Lezak, M.D., 2004. Neuropsychological Assessment. Oxford University Press.

Poldrack, R.A., Kittur, A., Kalar, D., Miller, E., Seppa, C., Gil, Y., Parker, D.S., Sabb, F.W., Bilder, R.M., 2011. The Cognitive Atlas. www.cognitiveatlas.org.

Chapter 3

RESULTS

3.1 Younger Adults

3.1.1 Spatiotemporal Means and Variability

Results from the ANOVA test revealed significant changes for mean stride width at both self-selected and fast speeds when compared to the Baseline measure ($p<0.05$), but not for mean stride length or stride length or width variability in younger adults.

Post hoc adjustments following the ANOVA test revealed that neither the PASAT working memory task nor the Phone visual attention and fine motor skills task had a significant effect on any of the spatiotemporal means or variability when compared to Baseline ($p>0.05$) (Figure 3.1).

However, the SDMT visual attention and processing speed challenge revealed a significant increase in mean stride width at both self-selected ($p=0.034$) and fast speeds ($p=0.028$) when compared to the Baseline measure (Figure 3.1). A table of the results can be found in Appendix E.

None of the dual-task challenges showed a significant effect on mean stride length, stride length variability, or stride width variability for younger adults.

Although not all changes in spatiotemporal variables from the Baseline measure to the dual-tasks were significant, definite trends can be found through inspection within the data. As shown in Figure 3.1, mean stride width showed an

increasing trend from Baseline to all three dual-tasks at all three walking conditions. In addition, at self-selected speed, mean stride length decreased from the Baseline measure to all three of the dual-task conditions (Figure 3.1).

No definite trends can be found for stride width variability or stride length variability for the SDMT or Phone dual-task challenges (Figure 3.1). However, the PASAT working memory challenge consistently showed a lower variability than the Baseline measure for both stride width and length (Figure 3.1).

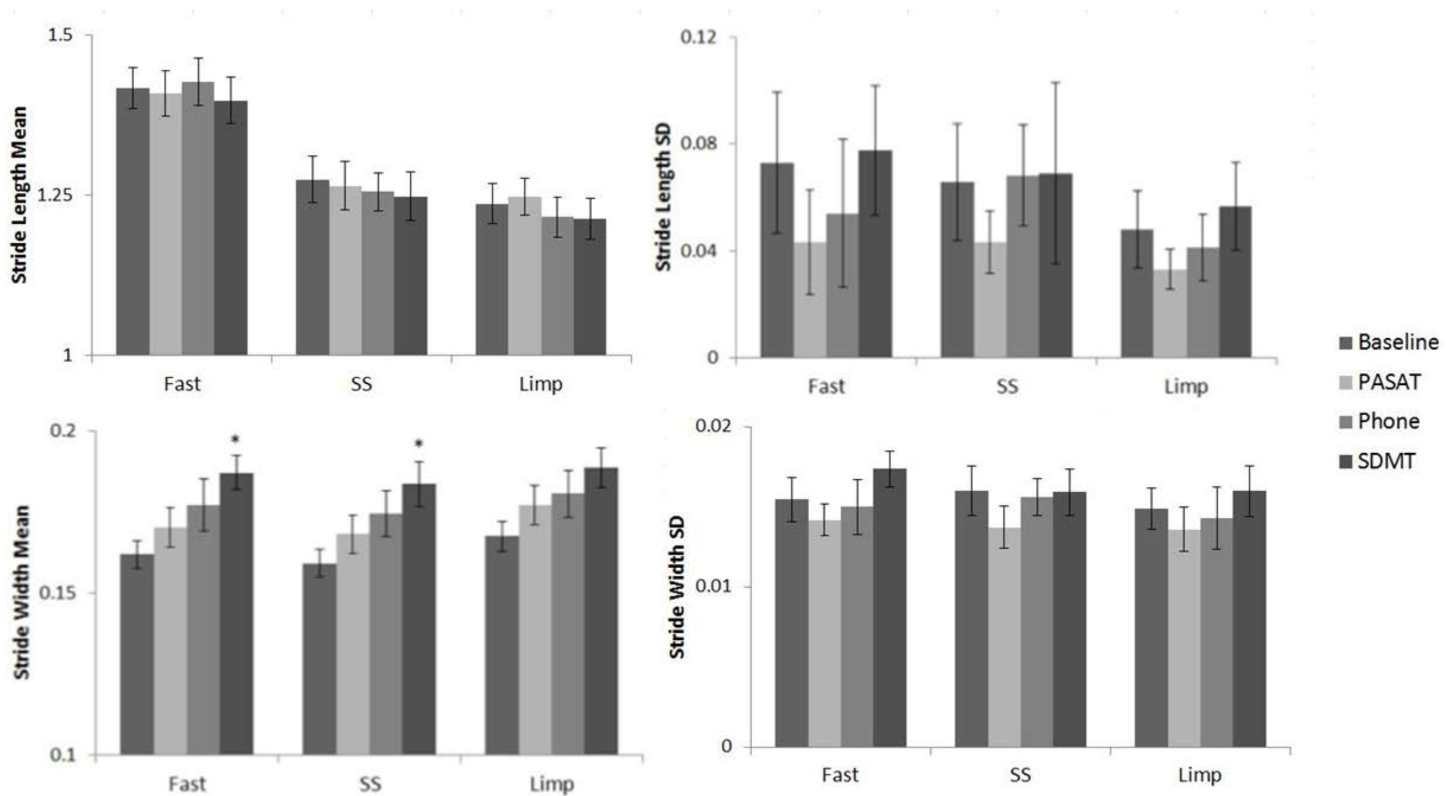

Figure 3.1: Stride length and width means and variability (m) for healthy younger adults at all dual-tasks at all three walking conditions. Error bars represent standard error. *: $p<0.05$ between dual-task and Baseline within the walking condition. SDMT: Visual attention task; PASAT: Working memory task.

3.1.2 Kinematics: Range of Motion and Variability

An ANOVA test did not reveal any significant differences for the range of motion of lower extremity joints in younger adults during dual-tasking across all speeds when compared to the Baseline measure ($p>0.05$). Post hoc adjustments also showed that no dual-task had a significant impact on the range of motion of the hip, knee, or ankle joint during any of the walking conditions ($p>0.05$) (Figure 3.2).

Likewise, ANOVA results and post hoc adjustments indicated that there were no significant differences in the variability of lower extremity range of motion between Baseline and dual-task conditions ($p>0.05$). The PASAT, SDMT, and Phone task did not significantly impact the variability of the hip, knee, or ankle motion at any of the walking conditions when compared to Baseline (Figure 3.2). A table of the results can be found in Appendix E.

Visible trends for the range of motion and variability of lower extremity joints, although not statistically significant, help to describe the impact of dual-tasking on the gait of healthy younger adults. As shown in Figure 3.2, the variability at the hip joint was lower for all three of the dual-tasks compared to the Baseline measure at all three walking conditions. The same trend occurs with the variability at the ankle joint where all of the dual-tasks had a lower variability than the Baseline measure at all three walking conditions (Figure 3.2). A similar trend of decreased variability was found for the knee joint, with the only exceptions being the SDMT task at the fast speed, and the Phone and SDMT tasks at self-selected speed (Figure 3.2).

No definite trends can be described for the hip, knee, or ankle range of motion. The mean results for the range of motion at the hip, knee, and ankle had less than a five degree difference between the Baseline measure and all three dual-tasks within each walking condition (Figure 3.2).

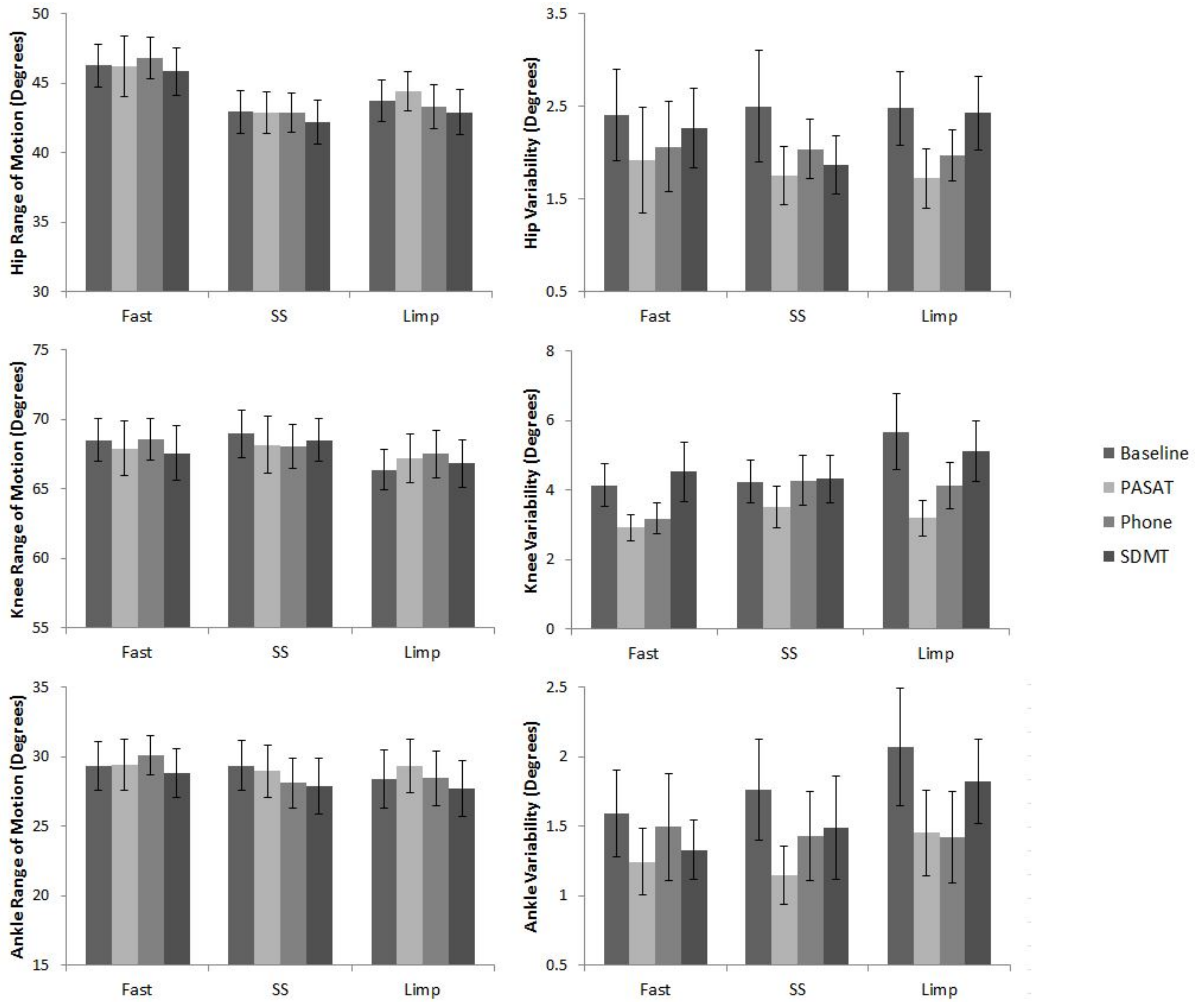

Figure 3.2: Hip, knee, and ankle joint range of motion and variability for healthy younger adults during dual-tasking at all three walking conditions. Error bars represent standard error. SDMT: Visual attention task; PASAT: Working memory task.

3.1.3 Kinetics and Kinematics: Peak Values

The ANOVA results for younger adults show that the peak values of kinetic and kinematic parameters were not significantly affected by the three different types of dual-tasking at any of the three walking conditions ($p>0.05$). Post hoc adjustments revealed that younger adults were not impacted by the addition of any of the dual-tasks for peak values for vertical ground reaction force, knee flexion during stance or swing, ankle plantar or dorsiflexion, hip extension during stance, or hip flexion during swing ($p>0.05$) (Figure 3.3). A table of the results can be found in Appendix E.

One visible trend in the peak kinematic data was found for knee flexion during stance. For all three walking conditions and all three types of dual-tasking, peak knee flexion during stance increased from the Baseline measure (Figure 3.3). In addition, there was a subtle decreasing trend for peak knee flexion during swing during all dual-tasks at all three walking conditions, with the only exceptions being the PASAT and Phone dual-tasks during the limp walking condition.

Within each walking condition, the mean values for peak vertical ground reaction force stayed approximately the same from the Baseline measure to all three dual-task challenges (Figure 3.3).

No visible trends were found for peak hip extension during stance, hip flexion during swing, ankle dorsiflexion, or ankle plantarflexion (Figure 3.3).

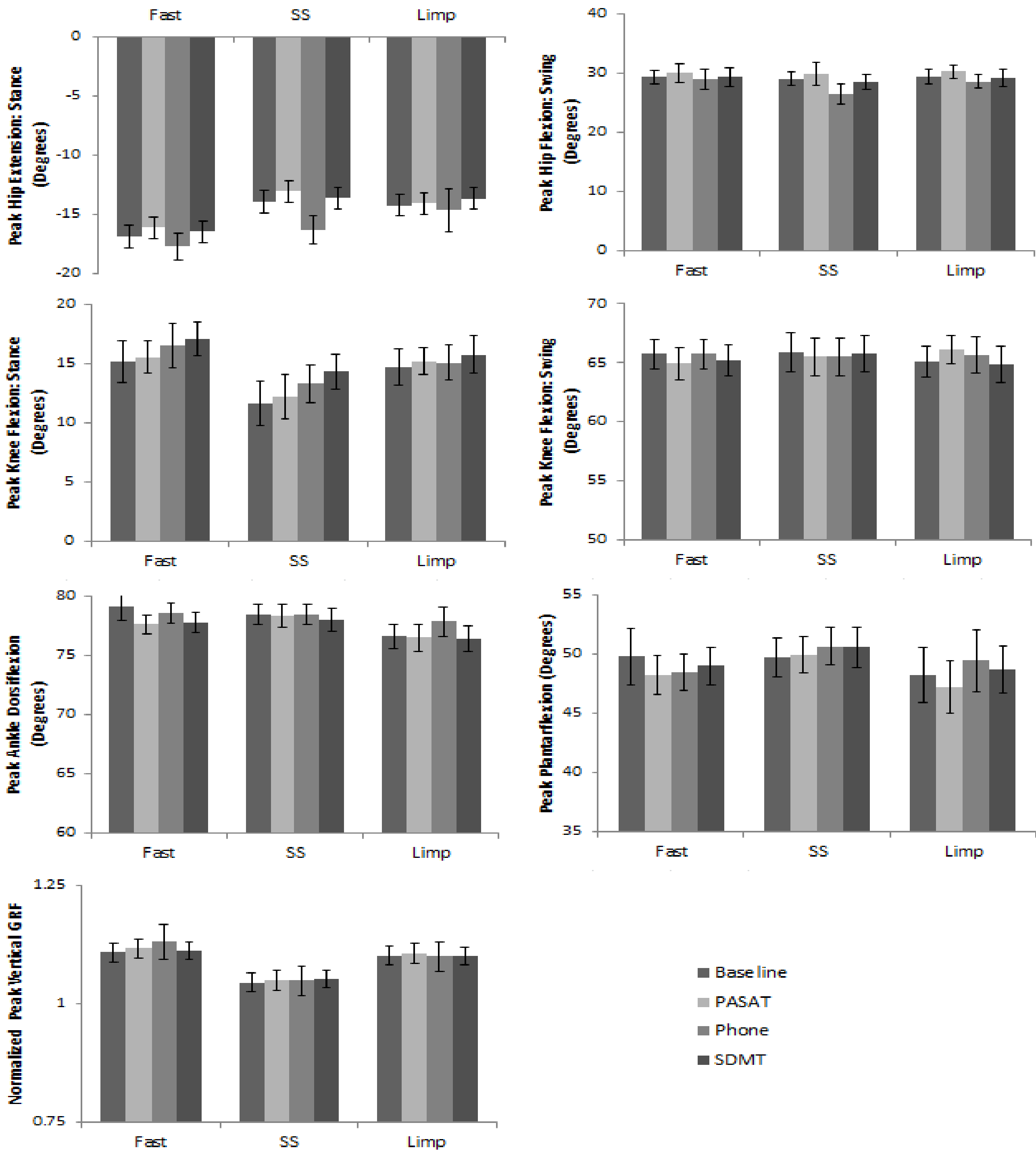

Figure 3.3: Peak kinematic and kinetic values for younger adults during dual-tasking at all three walking conditions. Error bars represent standard error. SDMT: Visual attention task; PASAT: Working memory task.

3.2 Older Adults

3.2.1 Spatiotemporal Means and Variability

In healthy older adults, stride length and width means and variability were not impacted by any type of dual-tasking at all three walking conditions when compared to Baseline, as shown by the ANOVA results ($p>0.05$).

Post hoc adjustments showed that the PASAT, SDMT, and Phone tasks did not have a significant impact on stride length and width means or variability at any of the three walking conditions ($p>0.05$). A table of the results can be found in Appendix F.

Although not statistically significant, visible trends can be found within the spatiotemporal measures for healthy older adults. For instance, mean stride length decreased from the Baseline measure to each of the dual-tasks for all walking conditions, with the only exception being the PASAT dual-task challenge at the fast speed (Figure 3.4).

In addition, mean stride width showed an increasing trend and stride width variability showed a decreasing trend between the Baseline measure and all three dual-task measures for all three walking conditions (Figure 3.4).

No visible trends can be found for stride length variability, except that the PASAT dual-task challenge consistently had a lower variability than the Baseline measure for all three walking conditions (Figure 3.4).

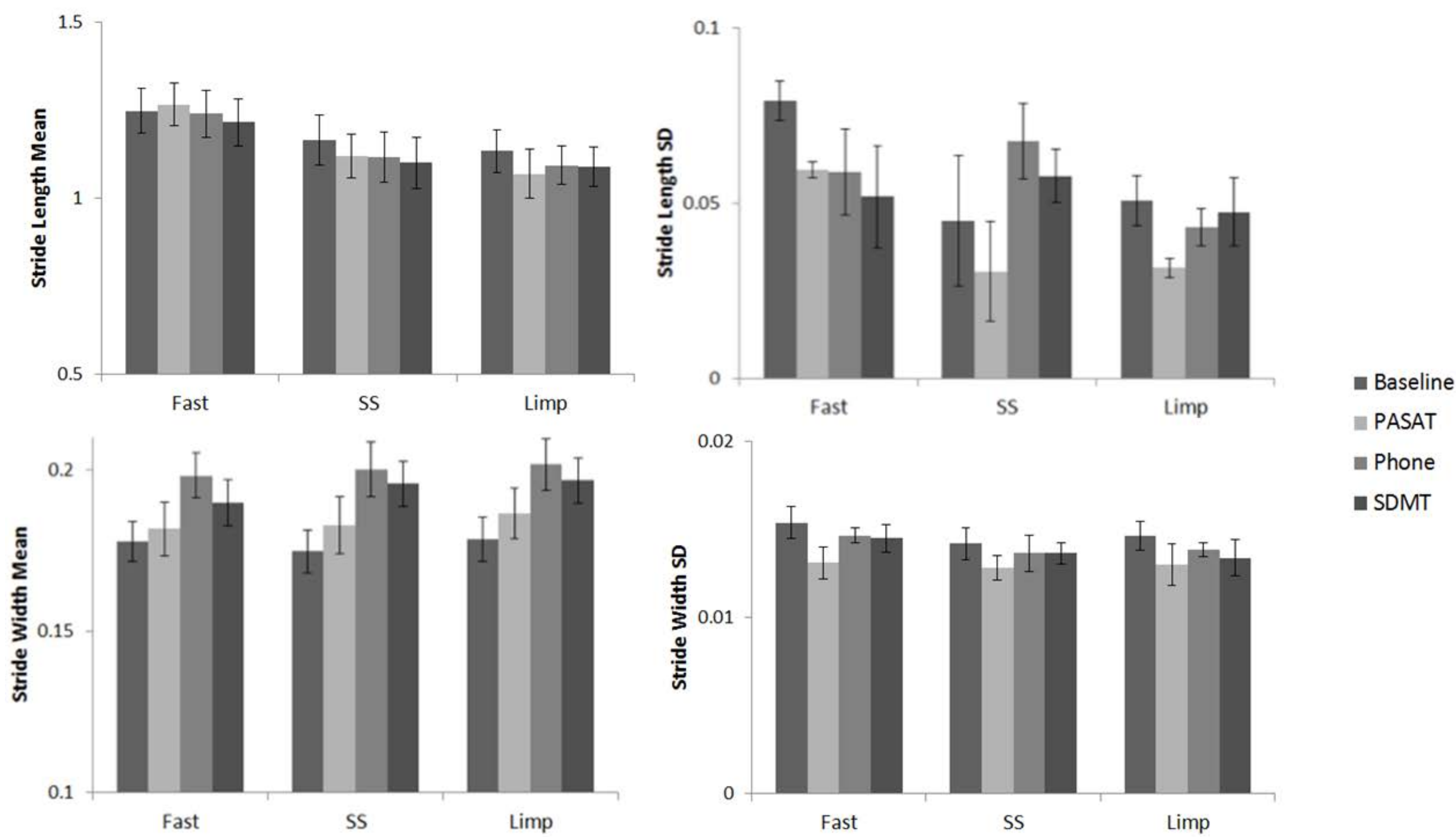

Figure 3.4: Stride length and width means and variability (m) for healthy older adults for all types of dual-tasking at all three walking conditions. Error bars represent standard error. SDMT: Visual attention task; PASAT: Working memory task.

3.2.2 Kinematics: Range of Motion and Variability

Results from the ANOVA test revealed no significant changes in hip, knee, and ankle range of motion across all walking conditions when compared to the Baseline measure ($p>0.05$). Post hoc adjustments also revealed that none of the three types of dual-tasks had an impact on hip, knee, or ankle range of motion ($p>0.05$).

In addition, range of motion variability in older adults during dual-tasking did not show a significant change according to an ANOVA test in hip, knee, and ankle range of motion variability at all three walking conditions ($p>0.05$). Post hoc adjustments showed that the PASAT, SDMT, and Phone dual-tasks did not have a significant impact on range of motion variability ($p>0.05$). A table of the results can be found in Appendix F.

Although not statistically significant, visible trends in the data include a consistent decreasing trend between the Baseline measure and all three types of dual-tasking at all three walking conditions for hip, knee, and ankle range of motion (Figure 3.5). There is only one exception where the dual-task had a higher range of motion than the Baseline measure, and that is with the Phone task at fast speed for ankle range of motion (Figure 3.5).

Lower extremity joint variability in healthy older adults did not display as clear of a trend as found for range of motion. For hip variability, the three dual-tasks had a lower variability than the Baseline measure for the fast and limp walking conditions. However, at self-selected speed, the variability at the hip joint was higher for all three dual-task measures when compared to Baseline (Figure 3.5).

The results for the variability at the knee showed that the PASAT working memory challenge and the Phone visual attention and fine motor skills challenge had a lower variability than the Baseline measure for all three walking conditions. No visible trend was found for the SDMT visual attention and processing speed challenge for variability at the knee (Figure 3.5).

At the ankle, the PASAT task had a lower variability than the Baseline measure for all three walking conditions. Both the Phone task and the SDMT task had

approximately the same variability as the Baseline measure, with the exception of the decreased variability with the SDMT task at the limp walking condition (Figure 3.5).

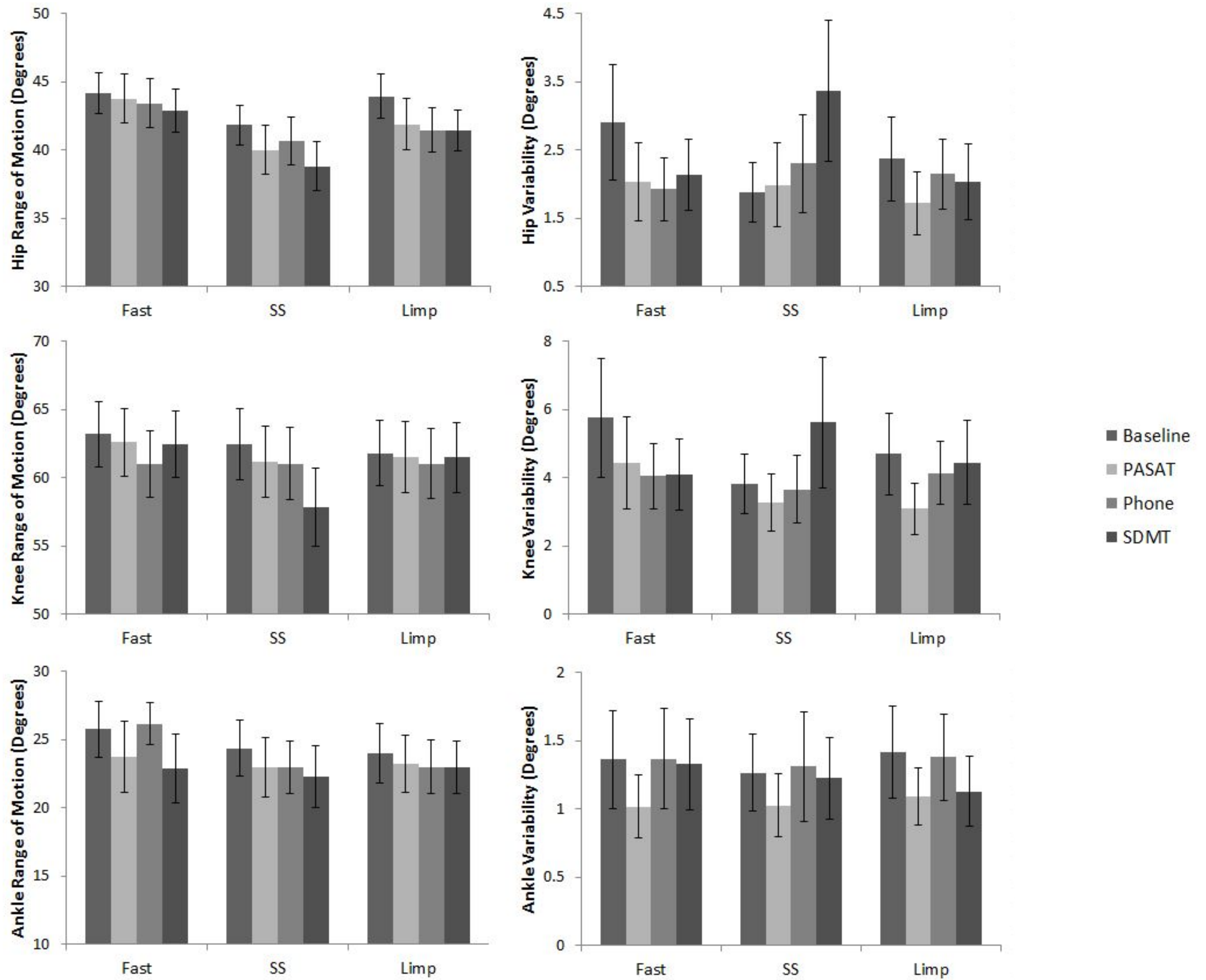

Figure 3.5: Hip, knee, and ankle joint range of motion and variability for healthy older adults during dual-tasking at all three walking conditions. Error bars represent standard error. SDMT: Visual attention task; PASAT: Working memory task.

3.2.3 Kinetics and Kinematics: Peak Values

The ANOVA results for older adults revealed that there was not a significant difference between Baseline and dual-task walking for lower extremity peak kinematic and kinetic values ($p>0.05$). Post hoc adjustments revealed that older adults were not impacted by the addition of any of the dual-tasks in terms of the peak values for vertical ground reaction force, knee flexion during stance or swing, ankle plantar or dorsiflexion, hip extension during stance, or hip flexion during swing ($p>0.05$). A table of the results can be found in Appendix F.

Although not statistically significant, trends for the peak values of kinetics and kinematics help to describe the effect of dual-tasking on older adults. First, the SDMT visual attention and processing speed task resulted in a decreased hip extension during stance for all three walking conditions (Figure 3.6). No visible trends were found for the PASAT or Phone dual-task conditions.

Peak hip flexion during swing showed that all three of the dual-task measures had a lower flexion than the Baseline measure for all three walking conditions (Figure 3.6).

In addition, peak knee flexion during stance was higher for all three of the dual-task measures when compared to Baseline for the fast and self-selected walking conditions (Figure 3.6). However, at the limp walking condition, peak knee flexion during stance remained approximately the same value across all dual-task conditions.

Peak ankle plantarflexion also displayed an increasing trend from the Baseline measure to all three dual-tasks at all walking conditions, the only exception being the Phone task at the fast walking condition (Figure 3.6).

No visible trend can be found for peak knee flexion during swing, peak ankle dorsiflexion, or peak vertical ground reaction force (Figure 3.6).

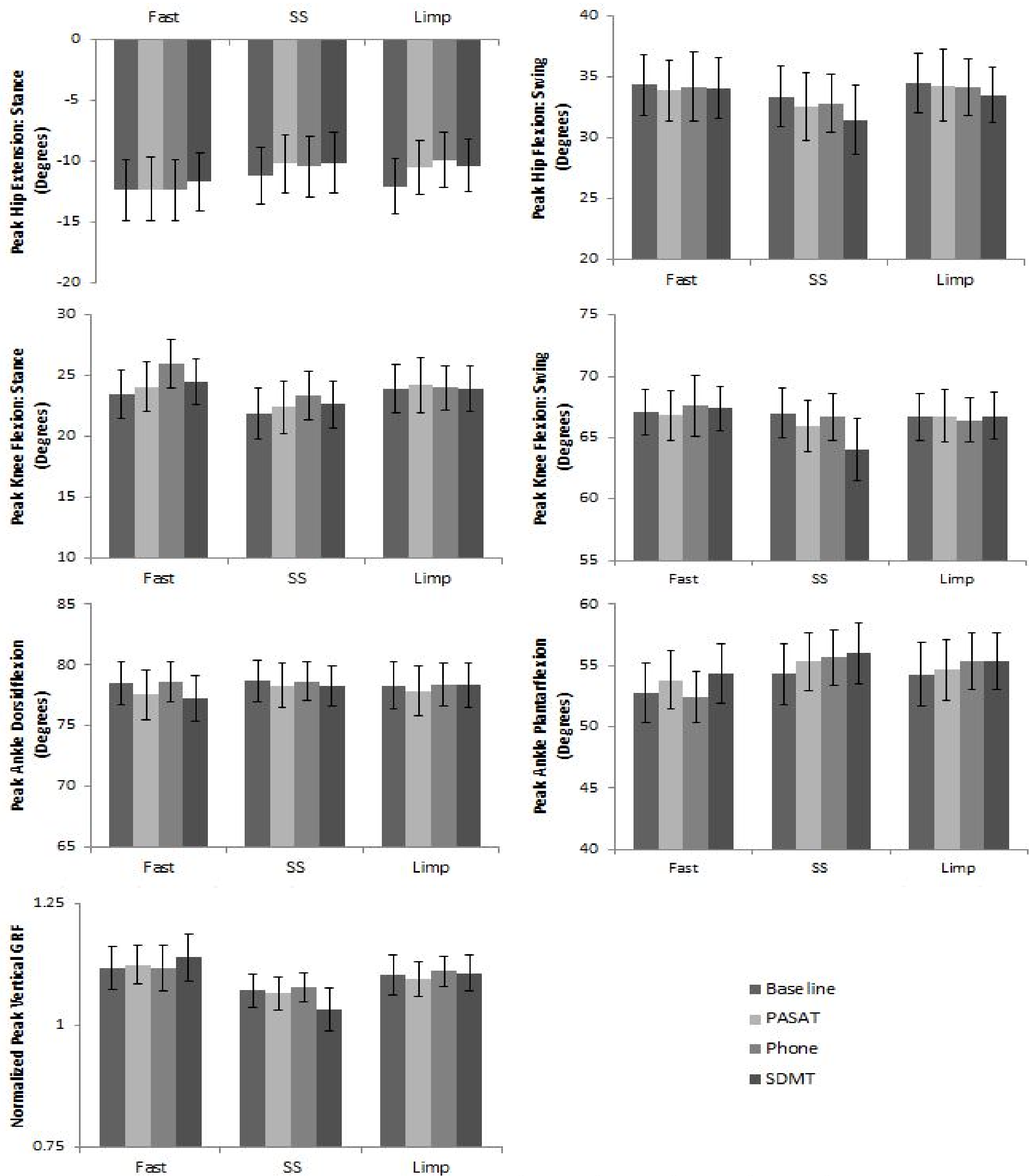

Figure 3.6: Peak kinematic and kinetic values for older adults during dual-tasking at all three walking conditions. Error bars represent standard error. SDMT: Visual attention task; PASAT: Working memory task.

Chapter 4

DISCUSSION

4.1 Younger and Older Adults

Because there is currently a limited understanding of the impact on kinetics, kinematics, and spatiotemporal variables under controlled speed conditions due to specific types of dual-task distractions for healthy younger and older adults, the objective of this study was to identify the trade-off between motor and cognitive tasks in terms of these gait parameters. Observing kinetic, kinematic, and spatiotemporal parameters allows for a more complete description of the effects of dual-tasking under controlled speed conditions.

The effect of dual-tasking under controlled speed conditions for both younger and older adults was minimal. Because significant changes in gait were only found for the mean stride width during the SDMT dual-task for younger adults under fast ($p = 0.028$) and self-selected ($p = 0.034$) walking conditions, the addition of a cognitive task did not seem to impact overall gait patterns for healthy younger or older adults. These results could be due to a number of different reasons. First of all, a number of parameters had a large effect size (>0.14), suggesting limited statistical power [Cohen, 1988]. This could be due to large standard deviations within the sample, or small sample size. The sample size for older adults was one greater than suggested by the a priori power analysis, but the sample size for younger adults was three smaller than suggested. A second power analysis was performed for all parameters following data collections that resulted in an average required sample size of forty-four younger adults and forty-three older adults.

Furthermore, our participants may have adopted a “posture-first” strategy, one of the expected compensations during dual-tasking [Bootsma-van der Wiel et al., 2003]. Under a posture-first strategy, participants are expected to maintain a normal gait pattern, but have the cognitive task performance suffer, indicating a prioritization of the motor task. Even though cognitive test scores have not yet been reported, the consistency of the gait patterns under these challenging motor and cognitive situations alludes to the possibility of a posture-first strategy. Preliminary results from cognitive testing indicate that participants generally performed better while seated than during the walking trials for the SDMT visual attention task, but performed at about the same level for the Phone and PASAT challenges. This could indicate that a posture-first strategy was utilized during the SDMT task, and possibly that the Phone and PASAT tasks were not challenging enough to show the effects of dual-tasking.

Also, under controlled speed conditions, participants had to compensate for a situation in which they would normally slow their walking speed. It has been previously reported that walking speed and kinematic parameters are often confounded. For instance, with increased walking speed, the angle during the total hip flexion-extension cycle increases, peak ankle dorsiflexion and plantarflexion increase, and peak knee flexion during stance and swing increase [Murray et al., 1984; Roislien et al., 2009]. Therefore, keeping a constant walking speed also led to consistent gait patterns under dual-task conditions.

In addition, this study recruited from only healthy younger and older adult populations. It is not surprising that these groups were able to maintain normal gait patterns, even under slightly more challenging conditions. It is probable that populations with gait or cognitive impairments would show more effects of dual-

tasking than the healthy populations included in this study. Furthermore, our older sample (60.5 ± 9.4 years) on average did not fall into the category of older adult, defined as individuals over 65 [Gobbo et al., 2014]. This could possibly indicate that changes in gait and cognitive abilities expected in an older adult population did not occur for the sample included in this study. Dual-task effects are expected to be different in elderly populations rather than a more middle-aged population [Coppin et al., 2006].

Finally, dual-task effects may be related to obstacle avoidance rather than to changes in gait parameters. Woollacott et al. suggested that it is the diminished ability to respond to hazards or obstacles in the environment that cause falls within the elderly population [Woollacott et al., 2002]. Therefore, obstructed vision and distraction in addition to obstacles in the path may be the cause of dual-task related accidents such as those found during texting and walking or falls in older adulthood.

However, even though the changes in gait due to dual-tasking were for the most part insignificant, the trends that were found in the data align with the parameters previously determined as indicative of falls. Parameters that have been found to be linked to falls include decreased stride length, increased stride width, increased stride length and width variability, and decreased hip and knee range of motion [VanSwearingen et al., 1996; Wolfson et al., 1990]. In this study, both younger and older adults displayed a trend of decreasing stride length and increasing stride width with the addition of all three dual-tasks under all three walking conditions. In addition, younger adults showed an increase in stride length and width variability under all three walking conditions for the SDMT dual-task challenge, possibly indicating that visual attention tasks also impact younger adults more than the other dual-task challenges.

Finally, older adults showed a decrease in hip and knee range of motion with the addition of all three dual-tasks at all three walking conditions. Because these trends are displayed for both healthy younger and older adults, it is probable that elderly or cognitively impaired populations would show significant changes in these parameters while dual-tasking, which could put vulnerable populations at risk for a fall.

Lövdén et al. observed the effects of dual-tasking under controlled speed conditions by observing stride-to-stride variability parameters and found that stride-to-stride variability was lower during dual-tasking with a working memory task compared to Baseline. In addition, they found that a working memory task decreased stride length variability in only younger adults [Lövdén et al., 2008]. In this study, the results for stride-to-stride variability were not significant, and therefore we cannot comment on the effect of specific tests. However, like Lövdén et al., this study also observed a decreasing trend for the working memory task (PASAT) for stride length and width variability in younger and older adults.

In addition to stride-to-stride variability, both groups showed a decrease from Baseline to the PASAT working memory task for hip, knee, and ankle range of motion variability. The only exception was for hip variability at self-selected speed for older adults. The fact that this decrease occurred at all lower extremity joints and for all spatiotemporal variability measures for all walking conditions for both groups could indicate the implementation of a stiffer walking pattern during the working memory task.

Most other dual-task studies observe the effect on gait due to an additional cognitive load by walking over-ground. In these studies, subjects typically reduced their walking speed, which was not possible in our experimental design using a

treadmill to control for speed. For instance, the main outcome measure for Bock et al. and Srygley et al. was gait velocity, and they reported a significant decrease in gait velocity for younger and older adults under dual-task conditions [Bock et al., 2008; Srygley et al., 2008]. Likewise, Coppin et al. and Montero-Odasso et al. reported decreased gait velocity under dual-task conditions for older adults [Coppin et al., 2006; Montero-Odasso et al., 2009]. Slightly expanding from a main outcome measure of gait velocity alone, a decrease in gait velocity paired with an increase in stride variability for participants under dual-task conditions was reported by Priest et al. for younger and older adults, and by Van Iersel et al for older adults [Priest et al., 2008; Reelick et al., 2009; Van Iersel et al., 2008]. The increased stride variability observed in previous studies was not found in this present study, probably due to the controlled treadmill speed in our study.

An interesting finding was reported by Reelick et al. who tested participants with and without a fear of falling under dual-task conditions. The results initially displayed a decrease in gait velocity and an increase in stride-length variability, similar to the results of the aforementioned studies. However, after Reelick et al. standardized for gait velocity, all of these differences lost their significance [Reelick et al., 2009]. This directly relates to the present study because we have standardized for gait velocity through the use of a treadmill, and agree with their results that stride length variability is not influenced by a similar cognitive task.

4.2 Study Strengths and Limitations

The design of this study comes with a number of strengths, but also a few potential weaknesses which we have attempted to minimize. One possible problem is the potential for fatigue or practice effects from not randomizing the order of the one-

on-one cognitive session and the gait analysis treadmill session. While seated, subjects have the chance to practice the tasks that they will be asked to repeat once they get to the treadmill, which may cause practice effects. In addition, it is possible that participants may be mentally fatigued after the one-on-one session and not able to perform to their full potential on the cognitive tasks during the gait analysis session. However, fatigue and practice effects will affect all subjects the same way since they are asked to perform all of the same tasks. Since we are not testing for the effects of fatigue or practice effects, it was not necessary to randomize the order of the two sessions.

Another potential weakness of this study is that participants were not instructed to prioritize one of the dual-tasks. Because of this, some participants may have prioritized the walking task, and some others may have prioritized the cognitive task, resulting in different allocations of attentional demands. However, by not being instructed to prioritize one task over the other, the dual-task challenge mimics the tasks found in the real world where each person chooses their own method of prioritizing different tasks. Because of its potential to imitate real-life situations, not asking participants to prioritize in any way will show how attentional demands are shared between cognitive and motor tasks in a natural setting.

One strength of this study was the high number of gait cycles for each trial. Each of the twelve walking trials was 120 seconds long, leading to a great number of gait cycles per trial (>100 gait cycles). Analyzing the changes in gait parameters benefits from these long trials because a higher number of gait cycles allows for a proper description of how each subject responded to the different cognitive tasks because attention was divided for a few minutes rather than a few steps. In addition,

the accuracy of spatiotemporal variability directly corresponds to the number of collected gait cycles [Grabiner et al., 2005].

However, a corresponding weakness of this study is that learning from the beginning to the end of the trial has not been analyzed. Participants may improve cognitive performance or decline in cognitive performance, depending on learning effects or fatigue. Likewise, participants may alter gait patterns as they become more comfortable with the task and the required walking condition as the trial continues. Because timing of responses was not measured explicitly throughout the trial and all gait cycles were analyzed for each trial, these effects can only be assumed as minimal.

Another strength of this study was the inclusion of an ecological validity dual-task as well as two classic cognitive measures. Not only were we able to measure the effect of specific aspects of cognition through the classic cognitive measures, but we can also see how each subject responded to a task that is commonly found in real life. Additionally, the effects of texting while walking are extremely relevant today, as evidenced by its constant presence in the media. The dangers of texting while walking have been exposed in the New York Times Magazine, US News, CNN, and USA Today in the first three months of 2014 alone [Reynolds, 2014; Preidt, 2014; Griggs, 2014; Watson, 2014].

One final strength of this study was controlling for walking speed. Furthermore, we challenged participants by asking them to dual-task at three different speeds. Previous studies have allowed for the personal selection of gait speed through over-ground dual-task challenges, and observed that participants slow their gait speed in order to compensate for additional cognitive tasks [Bock et al., 2008; Priest et al., 2008; Srygley et al., 2009; Van Iersel et al., 2008]. By using the treadmill to control

for walking speed, we could manipulate the complexity of the cognitive task as well as the complexity of the motor task in order to try to expose the interaction between a complex motor and a complex cognitive task.

Very few dual-task studies utilize a treadmill to control speed and length of trial, while there are many over-ground studies testing for the effects of dual-tasking over short distances. Lövdén et al conducted a dual-task study with controlled speed on a treadmill, however, each trial was only thirty seconds long which doesn't provide significantly more gait cycles than the typical over-ground study [Lövdén et al., 2008]. Other dual-task studies conducted on a treadmill did so under varying speed, unlike this study that highlights the effects of controlled speed with a high number of gait cycles [Abernethy et al., 2002; Barak et al., 2006]. Using the treadmill to control for speed over a long period of dual-tasking was a major strength of this study that to our knowledge has not yet been addressed in the literature.

4.3 Future Directions and Clinical Implications

The next logical step for this study includes testing a larger sample of healthy younger and older adults, and possibly utilizing more challenging cognitive measures. For instance, rather than typing a phone number visually presented as in the Phone task, perhaps participants could be challenged by texting a pre-determined sentence. In this way, the effects of texting while walking under controlled speed conditions could be revealed. In addition, a larger sample size would increase the statistical power of this study.

Another future direction for this study would be to test with the same methodology and procedures on the elderly or cognitively impaired. Testing these populations in order to compare the results to the healthy population included in this

study would reveal the effects of dual-tasking on those at risk for falls or injury. Again, while controlling the speed during dual-tasking, changes in gait parameters not confounded by gait speed will be revealed.

The results from this dual-tasking study for healthy younger and older adults while under controlled speed conditions have many clinical implications. First of all, a clinician could allow healthy younger and older adults to dual-task between a challenging motor and cognitive task without the fear of a risk of serious injury or fall. However, since the trends of the healthy younger and older adults align with the parameters indicative of a fall during all types of dual-tasks and of a stiffer walking pattern during a working memory task, caution should be taken when dual-tasking with the elderly or cognitively impaired [VanSwearingen et al., 1996; Wolfson et al., 1990]. A clinician may also suggest that the elderly or cognitively impaired avoid dual-tasking on a regular basis. Finally, since the ability to dual-task is known to improve with practice, dual-tasking in the elderly and cognitively impaired should first be studied in a controlled speed environment and then used as a learning tool to reduce the risk of injury [Bock, 2008].

REFERENCES

Abernethy, B., Hanna, A., Plooy, A., 2002. The Attentional Demands of Preferred and Non-Preferred Gait Patterns. Gait & Posture 15, 256–265.

Barak, Y., Wagenaar, R.C., Holt, K.G., 2006. Gait Characteristics of Elderly People with a History of Falls: A Dynamic Approach. Physical Therapy 86, 1501–1510.

Bock, O., 2008. Dual-Task Costs While Walking Increase in Old Age for Some, but Not for Other Tasks: An Experimental Study of Healthy Young and Elderly Persons. Journal of Neuroengineering and Rehabilitation 5, 27.

Bock, O., Engelhard, K., Guardiera, P., Allmer, H., Kleinert, J., 2008. Gerontechnology and Human Cognition: Impact of Cognitive Decay on the Ability to Operate Remote-Controlled Devices While Walking. IEEE Engineering in Medicine and Biology 27, 23–28.

Bootsma-van der Wiel, A., Gussekloo, J., de Craen, A.J.M., van Exel, E., Bloem, B.R., Westendorp, R.G.J., 2003. Walking and Talking as Predictors of Falls in the General Population: The Leiden 85-Plus Study. Journal of the American Geriatrics Society 51, 1466–1471.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences (2nd ed.). Hillsdale, NJ: Erlbaum.

Coppin, A.K., Shumway-Cook, A., Saczynski, J.S., Patel, K.V., Ble, A., Ferrucci, L., Guralnik, J., 2006. Association of Executive Function and Performance of Dual-Task Physical Tests Among Older Adults: Analyses from the InChianti Study. Age and Ageing 35, 619-624.

Gobbo, S., Bergamin, M., Sieverdes, J.C., Ermolao, A., Zaccaria, M., 2014. Effects of Exercise on Dual-Task Ability and Balance in Older Adults: A Systematic Review. Archives of Gerontology and Geriatrics 58, 177-187.

Grabiner, M.D., Troy, K.L., 2005. Attention Demanding Tasks During Treadmill Walking Reduce Step Width Variability in Young Adults. NeuroEngineering and Rehabilitation 2, 25.

Griggs, B., 2014. Study: Texting While Walking Affects Your Balance. CNN.

Lövdén, M., Schaefer, S., Pohlmeyer, A.E., Lindenberger, U., 2008. Walking Variability and Working-Memory Load in Aging: A Dual-Process Account Relating Cognitive Control to Motor Control Performance. Gerontology 63, 121–128.

Montero-Odasso, M., Bergman, H., Phillips, N.A., Wong, C.H., Sourial, N., Chertkow, H.,2009. Dual-Tasking and Gait in People with Mild Cognitive Impairment. The Effect of Working Memory. BMC Geriatrics 9, 41.

Murray, M.P., Mollinger, L.A., Gardner, G.M., Sepic, S.B., 1984. Kinematic and EMG Patterns During Slow, Free, and Fast Walking. Journal of Orthopaedic Research 2, 272-280.

Preidt, R., 2014. Texting While Walking Often Leads to Injuries: Expert. U.S.News: HealthDay.

Priest, A.W., Salamon, K.B., Hollman, J.H., 2008. Age-Related Differences in Dual Task Walking: A Cross Sectional Study. Journal of Neuroengineering and Rehabilitation 5, 29.

Reelick, M.F., Van Iersel, M.B., Kessels, R.P.C., Olde Rikkert, M.G.M., 2009). The Influence of Fear of Falling on Gait and Balance in Older People. Age and Ageing 38, 435–440.

Reynolds, G., 2014. The Art of Texting While Walking. The New York Times Magazine.

Roislien, J., Skare, O., Gustavsen, M., Broch, N.L., Rennie, L., Opheim, A., 2009. Simultaneous Estimation of Effects of Gender, Age and Walking Speed on Kinematic Gait Data. Gait & Posture 30, 441-445.

Srygley, J.M., Mirelman, A., Herman, T., Giladi, N., Hausdorff, J.M., 2009. When Does Walking Alter Thinking? Age and Task Associated Findings. Brain Research 1253, 92–99.

Van Iersel, M.B., Kessels, R.P.C., Bloem, B.R., Verbeek, A.L.M., Olde Rikkert, M.G.M., 2008. Executive Functions Are Associated with Gait and Balance in Community-Living Elderly People. Gerontology 63, 1344–1349.

VanSwearingen, J.M., Paschal, K.A., Bonino, P., Yang, J.F., 1996. The Modified Gait Abnormality Rating Scale for Recognizing the Risk of Recurrent Falls in Community-dwelling Elderly Adults. Physical Therapy 76, 994–1002.

Watson, T., 2014. You Can’t Walk Straight While Texting, Study Confirms. USA Today.

Wolfson, L., Whipple, R., Amerman, P., Tobin, J.N., 1990. Gait Assessment in the Elderly: a Gait Abnormality Rating Scale and Its Relation to Falls. Gerontology 45, M12–19.

Woollacott, M., Shumway-Cook, A., 2002. Attention and the Control of Posture and Gait: A Review of an Emerging Area of Research. Gait & Posture 16, 1–14.

REFERENCES

Abernethy, B., Hanna, A., Plooy, A., 2002. The Attentional Demands of Preferred and Non-Preferred Gait Patterns. Gait & Posture 15, 256–265.

Alexander, N.B., Hausdorff, J.M., 2008. Guest Editorial: Linking Thinking, Walking, and Falling. The Journals of Gerontology. 63, 1325–1328.

Barak, Y., Wagenaar, R.C., Holt, K.G., 2006. Gait Characteristics of Elderly People with a History of Falls: A Dynamic Approach. Physical Therapy 86, 1501–1510.

Bock, O., 2008. Dual-Task Costs While Walking Increase in Old Age for Some, but Not for Other Tasks: An Experimental Study of Healthy Young and Elderly Persons. Journal of Neuroengineering and Rehabilitation 5, 27.

Bock, O., Engelhard, K., Guardiera, P., Allmer, H., Kleinert, J., 2008. Gerontechnology and Human Cognition: Impact of Cognitive Decay on the Ability to Operate Remote-Controlled Devices While Walking. IEEE Engineering in Medicine and Biology 27, 23–28.

Bootsma-van der Wiel, A., Gussekloo, J., de Craen, A.J.M., van Exel, E., Bloem, B.R., Westendorp, R.G.J., 2003. Walking and Talking as Predictors of Falls in the General Population: The Leiden 85-Plus Study. Journal of the American Geriatrics Society 51, 1466–1471.

Brach, J.S., Berthold, R., Craik, R., VanSwearingen, J.M., Newman, A.B., 2001. Gait Variability in Community-Dwelling Older Adults. Journal of the American Geriatrics Society 49, 1646–1650.

Bridenbaugh, S.A., Kressig, R.W., 2011. Laboratory Review: The Role of Gait Analysis in Seniors' Mobility and Fall Prevention. Gerontology 57, 256–264.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences (2nd ed.). Hillsdale, NJ: Erlbaum.

Coppin, A.K., Shumway-Cook, A., Saczynski, J.S., Patel, K.V., Ble, A., Ferrucci, L., Guralnik, J., 2006. Association of Executive Function and Performance of Dual-Task Physical Tests Among Older Adults: Analyses from the InChianti Study. Age and Ageing 35, 619-624.

Daily Mail Reporter, 2013. Texting and Walking Blamed for the Nation-Wide Increase of Pedestrian Deaths. Daily Mail.

Diehr, M.C., Heaton, R.K., Miller, W., Grant, I., 1998. The Paced Auditory Serial Addition Task (PASAT): Norms for Age, Education, and Ethnicity. Psychological Assessment 5, 375-387.

Gobbo, S., Bergamin, M., Sieverdes, J.C., Ermolao, A., Zaccaria, M., 2014. Effects of Exercise on Dual-Task Ability and Balance in Older Adults: A Systematic Review. Archives of Gerontology and Geriatrics 58, 177-187.

Grabiner, M.D., Troy, K.L., 2005. Attention Demanding Tasks During Treadmill Walking Reduce Step Width Variability in Young Adults. NeuroEngineering and Rehabilitation 2, 25.

Griggs, B., 2014. Study: Texting While Walking Affects Your Balance. CNN.

Hausdorff, J.M., Rios, D.A., Edelberg, H.K., 2001. Gait Variability and Fall Risk in Community-Living Older Adults: A 1-Year Prospective Study. Archives of Physical Medicine and Rehabilitation 82, 1050–1056.

Lezak, M.D., 2004. Neuropsychological Assessment. Oxford University Press.

Liu-Ambrose, T, Katarynych, L.A., Ashe, M.C., Nagamatsu, L.S., Hsu, C.L., 2009. Dual-Task Gait Performance among Community-Dwelling Senior Women: The Role of Balance Confidence and Executive Functions. Gerontology 64, 975–982.

Lockhart, T.E., Woldstad, J.C., Smith, J.L., 2003. Effects of Age-Related Gait Changes on the Biomechanics of Slips and Falls. Ergonomics 46, 1136–1160.

Lockhart, T., Kim, S., Kapur, R., Jarrott, S., 2009. Evaluation of Gait Characteristics and Ground Reaction Forces in Cognitively Declined Older Adults With an Emphasis on Slip-Induced Falls. Assistive Technology : the Official Journal of RESNA 21, 188–195.

Lövdén, M., Schaefer, S., Pohlmeyer, A.E., Lindenberger, U., 2008. Walking Variability and Working-Memory Load in Aging: A Dual-Process Account Relating Cognitive Control to Motor Control Performance. Gerontology 63, 121–128.

Montero-Odasso, M., Bergman, H., Phillips, N.A., Wong, C.H., Sourial, N., Chertkow, H.,2009. Dual-Tasking and Gait in People with Mild Cognitive Impairment. The Effect of Working Memory. BMC Geriatrics 9, 41.

Murray, M.P., Mollinger, L.A., Gardner, G.M., Sepic, S.B., 1984. Kinematic and EMG Patterns During Slow, Free, and Fast Walking. Journal of Orthopaedic Research 2, 272-280.

Owings, T.M., Grabiner, M.D., 2004. Variability of Step Kinematics in Young and Older Adults. Gait & Posture 20, 26–29.

Parker-Pope, T., 2010. The Pedometer Test: Americans Take Fewer Steps. New York Times.

Perry, J., 1992. Gait Analysis: Normal and Pathological Function. SLACK Incorporated: Thorofare, NJ.

Plummer-D'Amato, P., Altmann, L.J.P., Saracino, D., Fox, E., Behrman, A.L., Marsiske, M., 2008. Interactions between Cognitive Tasks and Gait after Stroke: A Dual Task Study. Gait & Posture 27, 683–688.

Poldrack, R.A., Kittur, A., Kalar, D., Miller, E., Seppa, C., Gil, Y., Parker, D.S., Sabb, F.W., Bilder, R.M., 2011. The Cognitive Atlas. www.cognitiveatlas.org.

Preidt, R., 2014. Texting While Walking Often Leads to Injuries: Expert. U.S.News: HealthDay.

Priest, A.W., Salamon, K.B., Hollman, J.H., 2008. Age-Related Differences in Dual Task Walking: A Cross Sectional Study. *J*ournal of Neuroengineering and Rehabilitation 5, 29.

Reelick, M.F., Van Iersel, M.B., Kessels, R.P.C., Olde Rikkert, M.G.M., (2009). The Influence of Fear of Falling on Gait and Balance in Older People. *A*ge and Ageing 38, 435–440.

Reynolds, G., 2014. The Art of Texting While Walking. The New York Times Magazine.

Roislien, J., Skare, O., Gustavsen, M., Broch, N.L., Rennie, L., Opheim, A., 2009. Simultaneous Estimation of Effects of Gender, Age and Walking Speed on Kinematic Gait Data. Gait & Posture 30, 441-445.

Sparrow, W.A., Bradshaw, E.J., Lamoureux, E., Tirosh, O., 2002. Ageing Effects on the Attention Demands of Walking. Human Movement Science 21, 961-972.

Srygley, J.M., Mirelman, A., Herman, T., Giladi, N., Hausdorff, J.M., 2009. When Does Walking Alter Thinking? Age and Task Associated Findings. Brain Research 1253, 92–99.

Van Iersel, M.B., Kessels, R.P.C., Bloem, B.R., Verbeek, A.L.M., Olde Rikkert, M.G.M., 2008. Executive Functions Are Associated with Gait and Balance in Community-Living Elderly People. Gerontology 63, 1344–1349.

VanSwearingen, J.M., Paschal, K.A., Bonino, P., Yang, J.F., 1996. The Modified Gait Abnormality Rating Scale for Recognizing the Risk of Recurrent Falls in Community-dwelling Elderly Adults. Physical Therapy 76, 994–1002.

Watson, T., 2014. You Can't Walk Straight While Texting, Study Confirms. USA Today.

Wolfson, L., Whipple, R., Amerman, P., Tobin, J.N., 1990. Gait Assessment in the Elderly: a Gait Abnormality Rating Scale and Its Relation to Falls. Gerontology 45, M12–19.

Woollacott, M., Shumway-Cook, A., 2002. Attention and the Control of Posture and Gait: A Review of an Emerging Area of Research. Gait & Posture 16, 1–14.

Yang, Y.R., Chen, Y.C., Lee, C.S., Cheng, S.J., Wang, R.Y., 2006. Dual-Task-Related Gait Changes in Individuals with Stroke. Gait and Posture 25, 185-190.

Yogev-Seligmann, G., Hausdorff, J.M., Giladi, N., 2008. The Role of Executive Function and Attention in Gait. Movement Disorders 23, 329–342.

Zeni, J.A., Higginson, J.S., 2010. Gait Parameters and Stride-to-Stride Variability During Familiarization to Walking on a Split-Belt Treadmill. Clinical Biomechanics 25, 383-386.

Appendix A

CONSENT FORM

Consent to Participate in a Research Study

Title of Study: Linking Thinking and Walking
Primary Investigator:
(1) Jill Higginson, PhD; Department of Mechanical Engineering, University of Delaware;
Tel.: 302.831.6622; e-mail: higginson@udel.edu
(2) Christopher Higginson, Ph.D.; Department of Psychology, Loyola University Maryland;
Tel.: 410.617.2461; e-mail: cihigginson@loyola.edu

THIS PROTOCOL HAS BEEN REVIEWED AND APPROVED BY
THE UNIVERSITY OF DELAWARE AND LOYOLA UNIVERSITY MARYLAND INSTITUTIONAL REVIEW BOARD ON HUMAN SUBJECTS RESEARCH.

Purpose

You are being asked to participate in a research study involving walking on a treadmill and performing tasks used by psychologists to measure attention, reasoning, problem solving, and other types of thinking. From this study we hope to understand which tasks interfere with walking which may help to identify which individuals have an increased risk of falling.

Procedures

If you decide to volunteer for this study, we will ask you to complete a number of different tasks that involve attention, reasoning, problem solving, planning and spatial skills while you are seated quietly. The tasks are similar to the "brain-teaser" puzzles that are often found in newspapers. In some of the tasks you will verbally answer questions based on information that you hear or see. In other tasks you will have to use

a pencil and paper or other materials such as blocks. We will also ask you to complete questionnaires involving your mood and balance.

The next part of the study will occur in the biomechanics lab and you will be asked to wear shorts, t-shirt and comfortable walking shoes. We will measure your weight and height and comfortable walking speed by timing your pace in the hallway. While you are seated, we will attach reflective markers to your legs and upper body with tape. We will then ask you to walk on the treadmill in three different conditions: normal, fast, and with a limp. Finally, we will ask you to walk in the three conditions while completing thinking tests: a simple test, a more difficult test, and one involving the use of a cordless telephone. You may complete up to 12 different trials, each lasting up to two minutes, presented in random order. You will have ample time to rest between trials. We may also collect video for comparison with the motion data. These tasks will take about three hours in total to complete.

Risks

You may occasionally find some of the tasks cause a small amount of frustration that is not greater than the frustration ordinarily encountered in daily life. As with any physical activity, risks during walking include dizziness, heavy breathing and rapid heart rate. While walking on the treadmill, you will wear a protective harness and a handrail will be within reach.

You will receive first aid in the event of injury during this project. If you require additional medical treatment, you will be responsible for the cost.

Costs/Compensation

When your participation is complete you will receive a brief evaluation of your thinking skills by Dr. Christopher Higginson, a licensed psychologist. There are no costs to you for participation in this study.

Benefits

You will not personally benefit from your participation in this study. However, we hope to identify the effect of thinking tasks on walking performance and stability which may be useful in identifying individuals with an increased risk of falling.

Confidentiality

Any information obtained in connection with this study will be used in a manner that does not publicly disclose your identity and will be kept confidential; however, absolute confidentiality cannot be guaranteed, since there are a number of situations in which we may be legally required to disclose some of the information that we gather during the study (for example, court order). Only the individual who administered the tasks to you and the principal investigators will know your identity. After your participation is complete your data will be stored along with a code number. Only the investigators will know the identity associated with the code numbers and this information will be kept in a separate location from the data. Although research assistants trained to maintain confidentiality may access your data, they will only know your code number, not your name. At the conclusion of the study, any video used to document your results will be deleted.

Your Right Not to Participate or to Withdraw

You may choose not to be in the study, or, if you agree to be in the study, you may withdraw from the study at any time. A decision not to participate or to withdraw from the study will not result in any negative consequences for you.

Questions
If you have questions at any time, please ask us. If you have additional questions later, contact either Dr. Jill Higginson at 302.831.6622 or higginson@udel.edu, or you can contact Dr. Christopher Higginson at 410.617.2461 or cihigginson@loyola.edu. In addition, you may contact the Institutional Review Board on Human Subjects Research (IRB) at Loyola University Maryland, which is concerned with protecting volunteers in research projects. You may contact the Loyola IRB through Nancy Dufau, Grants Development Coordinator, at 410.617.2004 or ndufau@loyola.edu, or the Chair of the University of Delaware Human Subjects Review Board at 302.831.2137.

Statement of Consent

The purpose of this study, procedures to be followed, risks and benefits have been explained to me. I have been allowed to ask the questions I have, and my questions have been answered to my satisfaction. I have been told whom to contact if I have additional questions. I have read this consent form and agree to volunteer as a

research subject in this study with the understanding that I may withdraw at any time. I have been told that I will be given a signed copy of this consent form.

____ ______________
Printed name & signature of participant or legal representative Date

____ ______________
Printed name & signature of test administrator Date

____
Video Consent

I will allow video to be taken during data collection. YES / NO Initial: ________

I will allow video to be used as part of educational presentations, provided that my identity is not revealed. YES / NO Initial: _______

Appendix B

INCLUSION/EXCLUSION CRITERIA

Summary
You are being asked to participate in a research study involving walking on a treadmill while performing tasks used by psychologists to measure memory, attention, problem solving, and other types of thinking. From this study we hope to understand which tasks interfere with walking which may help to identify which individuals have an increased risk of falling.

Read the following questions to the potential subjects:	YES	NO
1. Has your doctor ever said that you have heart problems or a heart murmur?	□	□
2. Do you ever suffer pains in your chest?	□	□
3. Do you ever pass out, have spells of severe dizziness, or experience a persistent, rapid or irregular heartbeat?	□	□
4. Has your doctor told you that you currently have high blood pressure for which you are not taking medication (systolic pressure greater than or equal to 160 mmHg. or diastolic pressure greater than or equal to 90 mmHg.)?	□	□
5. Do you smoke cigarettes?	□	□
6. Do you have diabetes?	□	□
7. Do you have a family history of heart disease in parents or siblings prior to the age of 55?	□	□
8. Has your doctor told you that you currently have high cholesterol for which you are not taking medication?	□	□
9. Have you had any muscle or bone injury which affects your ability to walk on a treadmill?	□	□

10. What is your approximate weight and height? BMI = 703 * [weight in lbs / (height in inches)^2] and must be less than 40 to participate		
11. Have you ever hit your head and lost consciousness for more than 10 minutes?	☐	☐
12. Have you ever had a stroke or other illness involving your brain?	☐	☐
13. Have you ever been diagnosed with a psychological illness (e.g, ADHD, depression)?	☐	☐
14. Is there any physical reason not mentioned here why you should not perform physical exertion? (pregnancy, injury, pain)	☐	☐

If potential subject answers "yes" to any of the above questions, then subject should not be selected to participate in this study.

Appendix C

MARKER PLACEMENT GUIDE

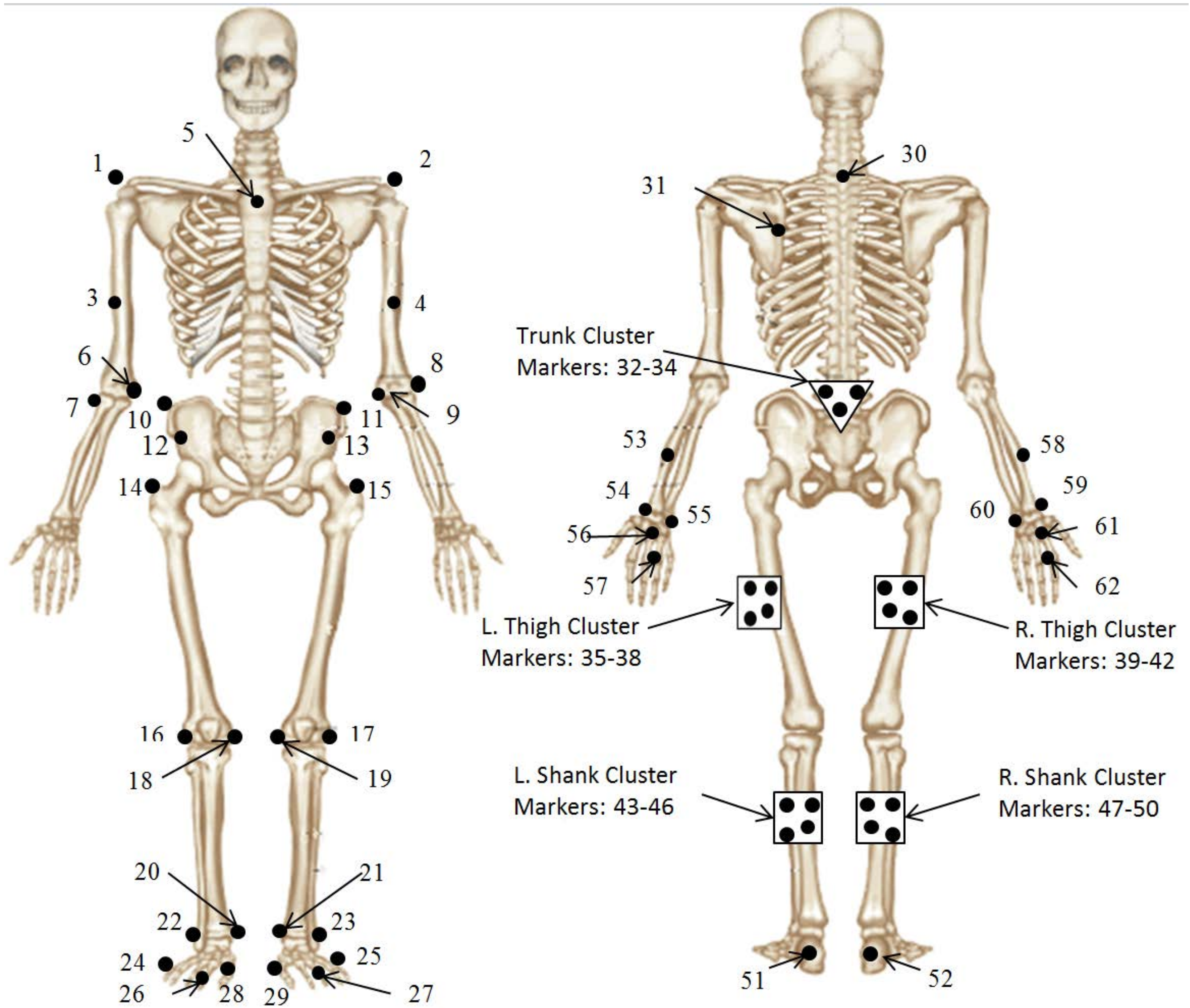

Figure C.1: Static marker set. Reflective markers placed on anatomical landmarks throughout the trunk, arms, pelvis, and legs.

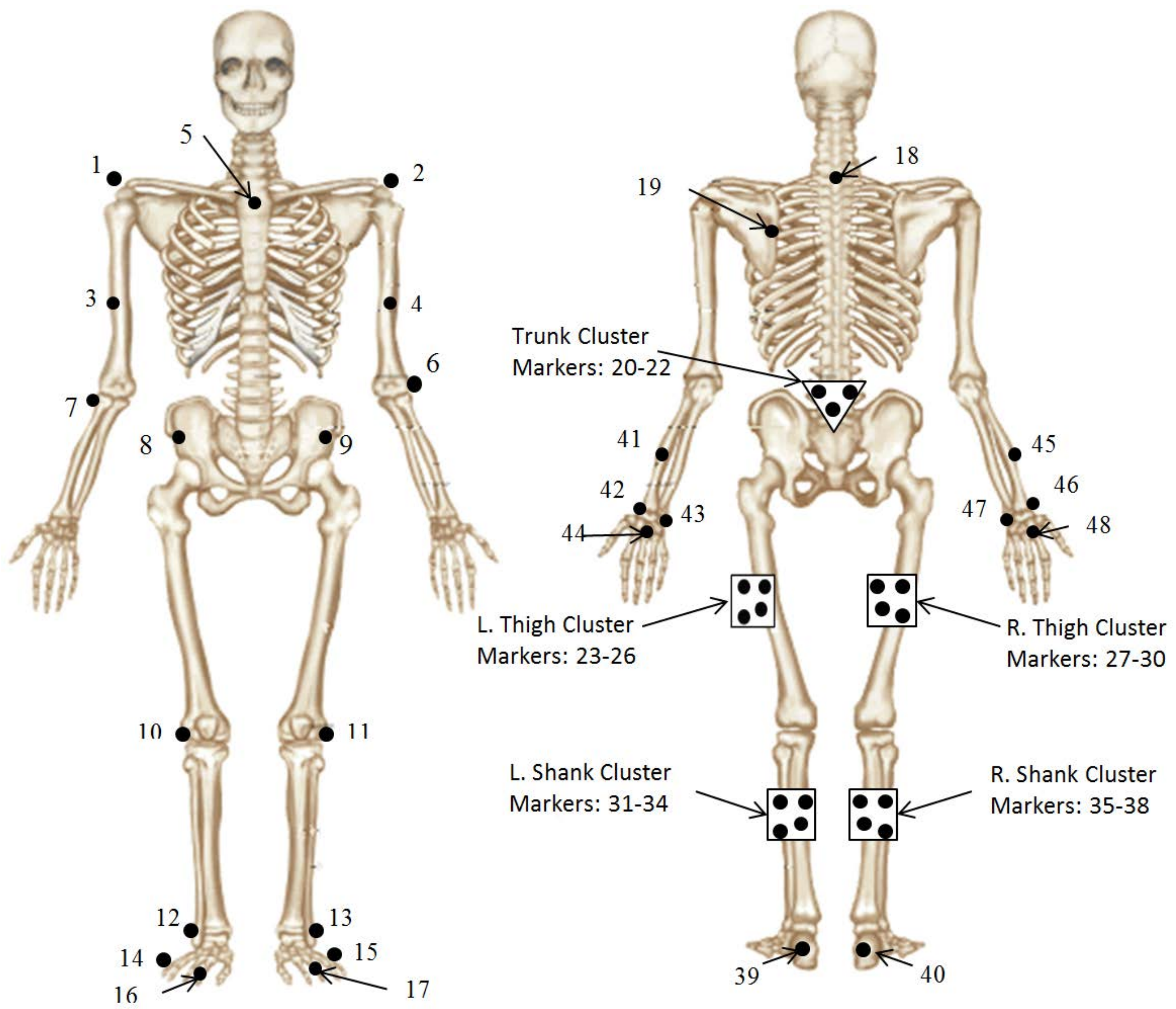

Figure C.2: Dynamic marker set. Medial and model building markers were removed from static marker set.

Appendix D

HUMAN SUBJECTS PROTOCOL: UNIVERSITY OF DELAWARE

Protocol Title: **Linking Thinking and Walking**

Principal Investigator
Name: Jill Higginson
Department/Center: Mechanical Engineering
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E-mail: cihigginson@loyola.edu

Investigator Assurance:

By submitting this protocol, I acknowledge that this project will be conducted in strict accordance with the procedures described. I will not make any modifications to this protocol without prior approval by the HSRB. Should any unanticipated problems involving risk to subjects, including breaches of guaranteed confidentiality occur during this project, I will report such events to the Chair, Human Subjects Review Board immediately.

1. **Is this project externally funded? NO.**

2. **Project Staff**
Please list personnel, including students, who will be working with human subjects on this protocol (insert additional rows as needed):

NAME	ROLE	HS TRAINING COMPLETE?
Jill Higginson	PI	Yes
Christopher Higginson	Co-PI	Yes (not at UD)
TBD	Graduate research assistant	

3. **Special Populations**
Does this project involve any of the following:
Research on Children? NO.
Research with Prisoners? NO.
Research with any other vulnerable population (please describe)? NO.

4. **RESEARCH ABSTRACT**
The purpose of this study is to compare walking performance while we ask healthy young and older adults to complete simple and complex thinking tasks. This study will involve walking on a treadmill while performing tasks commonly used by psychologists to measure attention, reasoning, problem solving, and other types of thinking. We will also ask participants to perform common daily activities such as operating a handheld cordless telephone. From this study we hope to understand which tasks interfere with walking which may help to identify those individuals who have an increased risk of falling.

5. **PROCEDURES**
Participants will be asked to complete a number of individually administered standardized clinical measures of attention, problem solving, planning, reasoning and spatial skills while seated in a quiet room. The tasks are similar to the "brain-teaser" puzzles that are often found in newspapers. In some of the tasks, subjects will verbally answer questions based on information that that is heard or seen. In other tasks, subjects will use a pencil and paper or other materials such as blocks. Subjects will also be asked to complete questionnaires involving their mood and balance.

The next part of the study will occur in the biomechanics lab and subjects will be asked to wear shorts, t-shirt and comfortable walking shoes. We will measure their weight and height and comfortable walking speed by timing their pace in the hallway. While the subject is seated, we will attach reflective markers to the legs and upper body with tape. The subject will walk on the treadmill in three different conditions:

normal, fast, and with a limp. Then they will be asked to walk in the three conditions while completing thinking tests: a simple test, a more difficult test, and one involving the use of a cordless telephone. Each subject may complete up to 12 different trials, each lasting up to two minutes, presented in random order, and will have ample time to rest between trials. We may also collect video for comparison with the motion data. These tasks will take about three hours in total to complete.

6. STUDY POPULATION AND RECRUITMENT

A total of 20 healthy young adults (aged 18-40 years) and 20 healthy older adults (aged 40-60 years) will be recruited. Men and women with no history of muscle, bone or nervous system disorders will participate in this study. All subjects will be recruited from the University of Delaware campus and other local areas.

Subjects will be asked questions about their overall health status to see if they are eligible to participate in the experiment. All subjects must sign an informed consent form approved by the Human Subjects Review Board of the University of Delaware. Any participant may withdraw from the study or the principal investigator may terminate the study at any time.

Subjects will be excluded they are currently pregnant or have a muscle, bone or nervous system disorder which affects their ability to walk safely on the treadmill. They will be asked a series of questions by phone to determine their ability to perform physical activities and will be excluded if the answers suggest they should have limited activity. In addition, we will estimate the body mass index which is a measure of body fat and must be less than 40 to participate.

7. RISKS AND BENEFITS

Subjects may occasionally find some of the tasks cause a small amount of frustration that is not greater than the frustration ordinarily encountered in daily life. As with any physical activity, risks during walking include dizziness, heavy breathing and rapid heart rate. While walking on the treadmill, subjects will wear a protective harness and a handrail will be within reach.

Subjects will receive first aid in the event of injury during this project. If additional medical treatment is required, subjects will be responsible for the cost.

Following participation, each subject will receive a screening evaluation of their cognitive function by the Co-PI, Dr. Christopher Higginson, a licensed clinical psychologist specializing in neuropsychology. Subjects will not personally benefit from participation in this study. However, we hope to identify the effect of thinking

tasks on walking performance and stability which may be useful in identifying individuals with an increased risk of falling.

8. **COMPENSATION**

Subjects will not be compensated for participating in this study, however each will receive a screening evaluation of their cognitive function by a licensed psychologist.

9. **DATA**

Personal information about subjects will remain confidential and will not be released (including any publication) without written consent. Data obtained from this study will be recorded on a computer without personal identifiers and archived indefinitely for use in future research studies.

10. **CONFIDENTIALITY**

All subject records will be kept private and used for research purposes only. They will be viewed by the research personnel only. Video will be acquired for comparison with the motion data. If video is to be used for educational presentations, the subject's identity will not be revealed.

11. **CONSENT and ASSENT**

_X__ Consent forms will be used and are attached for review.

____ Additionally, child assent forms will be used and are attached.
____ Consent forms will not be used (Justify request for waiver).

12. **Other IRB Approval**

This protocol will be submitted for review by Loyola University Maryland following approval by the University of Delaware.

13. **Supporting Documentation**

G&C protocol
G&C consent
G&C questionnaire

Appendix E

DATA TABLES: YOUNGER ADULTS

Table E.1: Spatiotemporal means and variability for healthy younger adults during dual-tasking. Mean (SD). Bolded values indicate significant difference between dual-task and baseline ($p<0.05$).

Self-Selected:

	Baseline	PASAT	Phone	SDMT
Stride Length Mean	1.27 (0.1)	1.26 (0.1)	1.26 (0.1)	1.25 (0.1)
Stride Length Variability	0.07 (0.1)	0.04 (0.1)	0.07 (0.1)	0.07 (0.1)
Stride Width Mean	0.16 (0.0)	0.17 (0.0)	0.17 (0.0)	**0.18 (0.0)**
Stride Width Variability	0.02 (0.0)	0.01 (0.0)	0.02 (0.0)	0.02 (0.0)

Fast:

	Baseline	PASAT	Phone	SDMT
Stride Length Mean	1.42 (0.1)	1.41 (0.1)	1.43 (0.1)	1.40 (0.1)
Stride Length Variability	0.07 (0.1)	0.04 (0.0)	0.05 (0.1)	0.08 (0.1)
Stride Width Mean	0.16 (0.0)	0.17 (0.0)	0.18 (0.0)	**0.19 (0.0)**
Stride Width Variability	0.02 (0.0)	0.01 (0.0)	0.02 (0.0)	0.02 (0.0)

Limp:

	Baseline	PASAT	Phone	SDMT
Stride Length Mean	1.24 (0.1)	1.25 (0.1)	1.22 (0.1)	1.21 (0.1)
Stride Length Variability	0.05 (0.0)	0.03 (0.0)	0.04 (0.0)	0.06 (0.1)
Stride Width Mean	0.17 (0.0)	0.18 (0.0)	0.18 (0.0)	0.19 (0.0)
Stride Width Variability	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)	0.02 (0.0)

Table E.2: Hip, knee, and ankle range of motion and variability for healthy younger adults during dual-tasking at all three walking conditions. Mean (SD).

Self-Selected:

	Baseline	**PASAT**	**Phone**	**SDMT**
Hip Range of Motion	42.94 (4.8)	42.88 (4.8)	42.85 (4.4)	42.19 (4.9)
Knee Range of Motion	68.96 (5.5)	68.17 (6.4)	68.02 (5.0)	68.48 (4.9)
Ankle Range of Motion	29.34 (5.7)	28.96 (5.9)	28.11 (5.6)	27.88 (6.2)
Hip Variability	2.50 (1.9)	1.75 (1.0)	2.04 (1.0)	1.87 (1.0)
Knee Variability	4.23 (1.0)	3.52 (1.9)	4.27 (2.3)	4.31 (2.2)
Ankle Variability	1.76 (1.2)	1.15 (0.7)	1.43 (1.0)	1.49 (1.2)

Fast:

	Baseline	**PASAT**	**Phone**	**SDMT**
Hip Range of Motion	46.28 (4.8)	46.22 (6.9)	46.81 (4.7)	45.83 (5.4)
Knee Range of Motion	68.49 (4.8)	67.90 (6.2)	68.57 (4.7)	67.57 (6.2)
Ankle Range of Motion	29.32 (5.5)	29.42 (5.8)	30.10 (4.4)	28.82 (5.6)
Hip Variability	2.41 (1.6)	1.92 (1.8)	2.06 (1.5)	2.27 (1.4)
Knee Variability	4.14 (1.9)	2.93 (1.2)	3.18 (1.4)	4.52 (2.7)
Ankle Variability	1.59 (1.0)	1.24 (0.8)	1.49 (1.2)	1.33 (0.7)

Limp:

	Baseline	**PASAT**	**Phone**	**SDMT**
Hip Range of Motion	43.72 (4.8)	44.39 (4.4)	43.29 (5.0)	42.91 (5.2)
Knee Range of Motion	66.37 (4.5)	67.18 (5.6)	67.50 (5.4)	66.83 (5.4)
Ankle Range of Motion	28.37 (6.6)	29.32 (6.0)	28.43 (6.3)	27.74 (6.3)
Hip Variability	2.48 (1.3)	1.72 (1.0)	1.97 (0.9)	2.42 (1.2)
Knee Variability	5.67 (3.4)	3.19 (1.7)	4.13 (2.1)	5.12 (2.8)
Ankle Variability	2.07 (1.3)	1.45 (1.0)	1.42 (1.0)	1.82 (1.0)

Table E.3: Peak kinematic and kinetic values for healthy younger adults during dual-tasking at all three walking conditions. Mean (SD).

Self-Selected:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Vertical GRF	1.05 (0.07)	1.05 (0.08)	1.05 (0.07)	1.05 (0.07)
Hip Extension Stance	-13.91 (3.7)	-13.04 (3.35)	-16.33 (5.9)	-13.63 (3.4)
Hip Flexion Swing	29.04 (3.7)	29.84 (6.1)	26.52 (5.6)	28.56 (3.7)
Knee Flexion Stance	11.67 (5.9)	12.22 (6.1)	13.30 (5.2)	14.33 (4.6)
Knee Flexion Swing	65.87 (5.4)	65.48 (5.2)	65.47 (5.2)	65.79 (4.9)
Ankle Dorsiflexion	78.44 (2.7)	78.38 (3.0)	78.47 (2.8)	78.05 (3.0)
Ankle Plantarflexion	49.72 (5.1)	49.98 (4.9)	50.68 (4.9)	50.60 (5.4)

Fast:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Vertical GRF	1.11 (0.1)	1.12 (0.1)	1.13 (0.1)	1.11 (0.1)
Hip Extension Stance	-16.93 (3.8)	-16.15 (3.77)	-17.74 (5.8)	-16.48 (3.7)
Hip Flexion Swing	29.35 (3.8)	30.07 (5.1)	29.07 (5.35)	29.36 (4.8)
Knee Flexion Stance	15.19 (5.4)	15.57 (4.4)	16.52 (6.0)	17.09 (4.4)
Knee Flexion Swing	65.73 (4.0)	64.90 (4.4)	65.73 (4.0)	65.21 (4.2)
Ankle Dorsiflexion	79.14 (3.7)	77.64 (2.6)	78.59 (2.6)	77.82 (2.8)
Ankle Plantarflexion	49.82 (7.6)	48.22 (5.2)	48.48 (4.9)	49.00 (5.0)

Limp:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Vertical GRF	1.10 (0.1)	1.11 (0.1)	1.10 (0.1)	1.10 (0.1)
Hip Extension Stance	-14.22 (4.8)	-14.07 (4.6)	-14.65 (4.6)	-13.65 (4.0)
Hip Flexion Swing	29.50 (4.0)	30.31 (3.6)	28.64 (3.7)	29.26 (4.8)
Knee Flexion Stance	14.73 (4.7)	15.20 (3.6)	15.12 (4.7)	15.78 (5.0)
Knee Flexion Swing	65.09 (4.1)	66.13 (3.8)	65.63 (4.9)	64.82 (4.9)
Ankle Dorsiflexion	76.62 (3.3)	76.50 (3.6)	77.90 (4.0)	76.47 (3.4)
Ankle Plantarflexion	48.25 (7.2)	47.18 (7.0)	49.47 (8.3)	48.73 (6.3)

Appendix F

DATA TABLES: OLDER ADULTS

Table F.1: Spatiotemporal means and variability for healthy older adults during dual-tasking at all three walking conditions. Mean (SD).

Self-Selected:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Stride Length Mean	1.16 (0.2)	1.12 (0.2)	1.12 (0.2)	1.10 (0.2)
Stride Length Variability	0.05 (0.0)	0.03 (0.0)	0.07 (0.0)	0.06 (0.0)
Stride Width Mean	0.17 (0.0)	0.18 (0.0)	0.20 (0.0)	0.20 (0.0)
Stride Width Variability	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)

Fast:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Stride Length Mean	1.25 (0.2)	1.27 (0.2)	1.24 (0.2)	1.21 (0.2)
Stride Length Variability	0.08 (0.1)	0.06 (0.0)	0.06 (0.0)	0.05 (0.0)
Stride Width Mean	0.18 (0.0)	0.18 (0.0)	0.20 (0.0)	0.19 (0.0)
Stride Width Variability	0.02 (0.0)	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)

Limp:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Stride Length Mean	1.13 (0.2)	1.07 (0.2)	1.09 (0.2)	1.09 (0.2)
Stride Length Variability	0.05 (0.0)	0.03 (0.0)	0.04 (0.0)	0.05 (0.0)
Stride Width Mean	0.18 (0.0)	0.19 (0.0)	0.20 (0.0)	0.20 (0.0)
Stride Width Variability	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)

Table F.2: Hip, knee, and ankle range of motion and variability for healthy older adults during dual-tasking at all three walking conditions. Mean (SD).

Self-Selected:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Hip Range of Motion	41.82 (4.8)	39.99 (6.0)	40.65 (5.8)	38.80 (6.0)
Knee Range of Motion	62.44 (8.6)	61.18 (8.7)	61.02 (8.8)	57.84 (9.5)
Ankle Range of Motion	24.34 (6.8)	22.94 (7.3)	22.98 (6.4)	22.27 (7.6)
Hip Variability	1.87 (1.4)	1.98 (2.0)	2.30 (2.4)	3.37 (3.4)
Knee Variability	3.82 (2.9)	3.26 (2.8)	3.66 (3.3)	5.61 (6.4)
Ankle Variability	1.27 (0.9)	1.02 (0.8)	1.31 (1.3)	1.22 (1.0)

Fast:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Hip Range of Motion	44.13 (5.0)	43.76 (6.0)	43.42 (6.0)	42.88 (5.3)
Knee Range of Motion	63.18 (7.9)	62.59 (8.1)	61.01 (8.1)	62.42 (8.1)
Ankle Range of Motion	25.74 (6.7)	23.72 (8.7)	26.13 (5.1)	22.88 (8.4)
Hip Variability	2.91 (2.8)	2.03 (1.9)	1.92 (1.5)	2.13 (1.8)
Knee Variability	5.76 (5.8)	4.44 (4.4)	4.05 (3.18)	4.09 (3.5)
Ankle Variability	1.36 (1.2)	1.02 (0.8)	1.37 (1.2)	1.33 (1.1)

Limp:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Hip Range of Motion	43.91 (5.4)	41.88 (6.1)	41.44 (5.4)	41.41 (5.1)
Knee Range of Motion	61.78 (7.9)	61.53 (8.6)	61.02 (8.5)	61.47 (8.4)
Ankle Range of Motion	24.00 (7.2)	23.20 (6.9)	22.98 (6.6)	22.96 (6.3)
Hip Variability	2.37 (2.0)	1.72 (1.5)	2.15 (1.7)	2.03 (1.8)
Knee Variability	4.69 (3.9)	3.08 (2.5)	4.14 (3.1)	4.44 (4.1)
Ankle Variability	1.41 (1.1)	1.09 (0.7)	1.38 (1.1)	1.13 (0.9)

Table F.3: Peak kinematic and kinetic values for healthy older adults during dual-tasking at all three walking conditions. Mean (SD).

Self-Selected:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Vertical GRF	1.07 (0.1)	1.07 (0.1)	1.08 (0.1)	1.03 (0.1)
Hip Extension Stance	-11.20 (7.8)	-10.21 (8.0)	-10.42 (8.3)	-10.12 (8.3)
Hip Flexion Swing	33.40 (8.3)	32.54 (9.2)	32.82 (7.9)	31.45 (9.4)
Knee Flexion Stance	21.89 (7.0)	22.40 (7.2)	23.37 (6.7)	22.64 (6.4)
Knee Flexion Swing	67.01 (6.8)	65.97 (6.9)	66.71 (6.3)	64.02 (8.3)
Ankle Dorsiflexion	78.65 (5.6)	78.28 (6.0)	78.62 (5.3)	78.25 (5.4)
Ankle Plantarflexion	54.31 (8.3)	55.34 (7.8)	55.64 (7.4)	55.98 (8.3)

Fast:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Vertical GRF	1.12 (0.1)	1.12 (0.1)	1.12 (0.2)	1.14 (0.2)
Hip Extension Stance	-12.37 (8.4)	-12.29 (8.8)	-12.37 (8.3)	-11.69 (7.9)
Hip Flexion Swing	34.35 (8.3)	33.90 (8.3)	34.21 (9.3)	34.09 (8.4)
Knee Flexion Stance	23.45 (6.6)	24.10 (6.9)	25.96 (6.6)	24.51 (6.1)
Knee Flexion Swing	67.07 (6.1)	66.80 (6.8)	67.60 (8.2)	67.38 (5.9)
Ankle Dorsiflexion	78.47 (6.0)	77.52 (6.8)	78.54 (5.5)	77.24 (6.3)
Ankle Plantarflexion	52.74 (8.0)	53.81 (7.7)	52.41 (6.9)	54.35 (8.0)

Limp:				
	Baseline	**PASAT**	**Phone**	**SDMT**
Vertical GRF	1.10 (0.1)	1.09 (0.1)	1.11 (0.1)	1.11 (0.1)
Hip Extension Stance	-12.08 (7.5)	-10.46 (7.4)	-9.92 (7.6)	-10.34 (7.3)
Hip Flexion Swing	34.47 (8.2)	34.31 (9.9)	34.13 (7.7)	33.51 (7.5)
Knee Flexion Stance	23.94 (6.6)	24.23 (7.5)	24.02 (6.0)	23.96 (6.1)
Knee Flexion Swing	66.68 (6.5)	66.75 (7.1)	66.44 (5.8)	66.78 (6.5)
Ankle Dorsiflexion	78.27 (6.3)	77.82 (6.9)	78.31 (5.9)	78.31 (6.1)
Ankle Plantarflexion	54.27 (8.5)	54.62 (8.1)	55.33 (7.7)	55.35 (7.6)

Appendix G

EFFECT SIZES

Table G.1: Effect sizes between cognitive conditions for younger adults (Y.A.) for all parameters at all speeds. Effect sizes were predominately large, with the exception of the spatiotemporal parameters and VGRF. Small: 0.01; Moderate: 0.04; Large: 0.14 [Cohen, 1988].

Age	Speed	Parameter	Effect	Effect Size
Y.A.	Limp	Ankle ROM	0.553	Large
Y.A.	Fast	Ankle ROM	0.450	Large
Y.A.	SS	Ankle ROM	0.604	Large
Y.A.	Limp	Ankle SD	0.271	Large
Y.A.	SS	Ankle SD	0.216	Large
Y.A.	Fast	Ankle SD	0.137	Moderate
Y.A.	Limp	Hip ROM	0.539	Large
Y.A.	Fast	Hip ROM	0.342	Large
Y.A.	SS	Hip ROM	0.305	Large
Y.A.	Limp	Hip SD	0.313	Large
Y.A.	Fast	Hip SD	0.187	Large
Y.A.	SS	Hip SD	0.287	Large
Y.A.	Limp	Knee ROM	0.422	Large
Y.A.	Fast	Knee ROM	0.415	Large
Y.A.	SS	Knee ROM	0.360	Large
Y.A.	Limp	Knee SD	0.939	Large
Y.A.	Fast	Knee SD	0.660	Large
Y.A.	SS	Knee SD	0.328	Large
Y.A.	Limp	Peak Hip Extension Stance	0.361	Large
Y.A.	Fast	Peak Hip Extension Stance	0.589	Large
Y.A.	SS	Peak Hip Extension Stance	1.256	Large
Y.A.	Limp	Peak Hip Flexion Swing	0.590	Large
Y.A.	Fast	Peak Hip Flexion Swing	0.371	Large
Y.A.	SS	Peak Hip Flexion Swing	1.226	Large

Table G.1 Continued:

Age	Speed	Parameter	Effect	Effect Size
Y.A.	Limp	Peak Knee Flexion Stance	0.380	Large
Y.A.	Fast	Peak Knee Flexion Stance	0.760	Large
Y.A.	SS	Peak Knee Flexion Stance	0.857	Large
Y.A.	Limp	Peak Knee Flexion Swing	0.500	Large
Y.A.	Fast	Peak Knee Flexion Swing	0.353	Large
Y.A.	SS	Peak Knee Flexion Swing	0.182	Large
Y.A.	Limp	Peak Dorsiflexion	0.600	Large
Y.A.	Fast	Peak Dorsiflexion	0.611	Large
Y.A.	SS	Peak Dorsiflexion	0.169	Large
Y.A.	Limp	Peak Plantarflexion	0.819	Large
Y.A.	Fast	Peak Plantarflexion	0.616	Large
Y.A.	SS	Peak Plantarflexion	0.410	Large
Y.A.	Limp	Stride Length Mean	0.014	Small
Y.A.	Fast	Stride Length Mean	0.010	Small
Y.A.	SS	Stride Length Mean	0.010	Small
Y.A.	Limp	Stride Length SD	0.009	Small
Y.A.	Fast	Stride Length SD	0.014	Small
Y.A.	SS	Stride Length SD	0.011	Small
Y.A.	Limp	Stride Width Mean	0.008	Small
Y.A.	Fast	Stride Width Mean	0.009	Small
Y.A.	SS	Stride Width Mean	0.009	Small
Y.A.	Limp	Stride Width SD	0.001	Small
Y.A.	Fast	Stride Width SD	0.001	Small
Y.A.	SS	Stride Width SD	0.001	Small
Y.A.	Limp	VGRF	0.002	Small
Y.A.	Fast	VGRF	0.008	Small
Y.A.	SS	VGRF	0.003	Small

Table G.2: Effect sizes between cognitive conditions for older adults (O.A.) for all parameters at all speeds. Effect sizes were predominately large, with the exception of the spatiotemporal parameters and VGRF. Small: 0.01; Moderate: 0.04; Large: 0.14 [Cohen, 1988].

Age	Speed	Parameter	Effect	Effect Size
O.A.	Limp	Ankle ROM	0.425	Large
O.A.	Fast	Ankle ROM	1.356	Large
O.A.	SS	Ankle ROM	0.753	Large
O.A.	Limp	Ankle SD	0.145	Large
O.A.	Fast	Ankle SD	0.147	Large
O.A.	SS	Ankle SD	0.109	Moderate
O.A.	Limp	Hip ROM	1.028	Large
O.A.	Fast	Hip ROM	0.461	Large
O.A.	SS	Hip ROM	1.093	Large
O.A.	Limp	Hip SD	0.236	Large
O.A.	Fast	Hip SD	0.387	Large
O.A.	SS	Hip SD	0.579	Large
O.A.	Limp	Knee ROM	0.274	Large
O.A.	Fast	Knee ROM	0.797	Large
O.A.	SS	Knee ROM	1.697	Large
O.A.	Limp	Knee SD	0.614	Large
O.A.	Fast	Knee SD	0.695	Large
O.A.	SS	Knee SD	0.891	Large
O.A.	Limp	Peak Hip Extension Stance	0.822	Large
O.A.	Fast	Peak Hip Extension Stance	0.284	Large
O.A.	SS	Peak Hip Extension Stance	0.424	Large
O.A.	Limp	Peak Hip Flexion Swing	0.361	Large
O.A.	Fast	Peak Hip Flexion Swing	0.166	Large
O.A.	SS	Peak Hip Flexion Swing	0.709	Large
O.A.	Fast	Peak Knee Flexion Stance	0.921	Large
O.A.	SS	Peak Knee Flexion Stance	0.534	Large
O.A.	Limp	Peak Knee Flexion Stance	0.116	Moderate
O.A.	Fast	Peak Knee Flexion Swing	0.306	Large
O.A.	SS	Peak Knee Flexion Swing	1.164	Large
O.A.	Limp	Peak Knee Flexion Swing	0.131	Moderate
O.A.	Limp	Peak Dorsiflexion	0.207	Large
O.A.	Fast	Peak Dorsiflexion	0.573	Large
O.A.	SS	Peak Dorsiflexion	0.186	Large
O.A.	SS	Peak Plantarflexion	0.624	Large

Table G.2 Continued:

Age	Speed	Parameter	Effect	Effect Size
O.A.	Limp	Peak Plantarflexion	0.464	Large
O.A.	Fast	Peak Plantarflexion	0.786	Large
O.A.	Limp	Stride Length Mean	0.023	Small
O.A.	Fast	Stride Length Mean	0.018	Small
O.A.	SS	Stride Length Mean	0.023	Small
O.A.	Limp	Stride Length SD	0.007	Small
O.A.	Fast	Stride Length SD	0.010	Small
O.A.	SS	Stride Length SD	0.014	Small
O.A.	Limp	Stride Width Mean	0.009	Small
O.A.	Fast	Stride Width Mean	0.008	Small
O.A.	SS	Stride Width Mean	0.010	Small
O.A.	Limp	Stride Width SD	0.003	Small
O.A.	Fast	Stride Width SD	0.001	Small
O.A.	SS	Stride Width SD	0.001	Small
O.A.	Limp	VGRF	0.006	Small
O.A.	Fast	VGRF	0.009	Small
O.A.	SS	VGRF	0.017	Small