1 ERRORS IN THE ANKLE PLANTARFLEXOR FORCE PRODUCTION ARE RELATED
2 TO THE GAIT DEFICITS OF INDIVIDUALS WITH MULTIPLE SCLEROSIS

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1 **Abstract**

2 *Background:* Individuals with multiple sclerosis (MS) often have limited mobility that
3 is thought to be due to the neuromuscular impairments of the ankle. Greater isometric
4 motor control of the ankle has been associated with better standing postural balance but
5 its relationship to mobility is less understood. The objectives of this investigation were to
6 quantify the motor control of the ankle plantarflexors of individuals with MS during a
7 dynamic isometric motor task, and explore the relationship between the ankle force
8 control and gait alterations.

9 *Methods:* Fifteen individuals with MS and 15 healthy adults participated in both a
10 dynamic isometric ankle plantarflexion force matching task and a biomechanical gait
11 analysis.

12 *Findings:* Our results displayed that the subjects with MS had a greater amount of error
13 in their dynamic isometric force production, were weaker, walked with altered
14 spatiotemporal kinematics, and had reduced maximal ankle moment at toe-off than the
15 control group. The greater amount of error in the dynamic force production was related
16 to the decreases in strength, step length, walking velocity, and maximal ankle moment
17 during walking.

18 *Interpretation:* Altogether these results imply that errors in the ankle plantarflexion force
19 production may be a limiting factor in the mobility of individuals with MS.

20 **Keywords: Walking, Torque, Isometric, Variability**

21

1.0 Introduction

Multiple sclerosis (MS) is a demyelinating disease that affects about 570,000 individuals in the United States (Campbell, et al., 2014). These individuals often face motor impairments that result from muscular weakness, latent muscular activity, spasticity, and muscular fatigue (Cameron, Horak, Herndon, & Bourdette, 2008; Lambert, Archer, & Evans, 2001; Ponichtera, Rodgers, Glaser, Mathews, & Camaione, 1992; Scheidegger, Kamm, Humpert, & Rosler, 2012; Sosnoff, Gappmaier, Frame, & Motl, 2011; Steens, Heersema, Maurits, Renken, & Zijdwind, 2012; Wagner, Kremer, Van Dillen, & Naismith, 2014). As a result of these motor deficits, individuals with MS often have balance limitations which make them highly susceptible to falling. It has been suggested that individuals with MS may compensate for their balance limitations by walking with shorter step lengths, slower walking velocities, slower cadences, and an increased amount of time spent in double support (Benedetti, et al., 1999; Kelleher, Spence, Solomonidis, & Apatsidis, 2010; Martin, et al., 2006). It has been speculated that the neuromuscular impairments in the ankle plantarflexor musculature, such as increased muscle weakness or poor motor control, have major effects on the mobility; however, this notion has not been well explored (Huisinga, Schmid, Filipi, & Stergiou, 2013; Kelleher, et al., 2010; Martin, et al., 2006; Sosnoff, et al., 2011; Wagner, et al., 2014).

Control of the ankle plantarflexor musculature can be quantified by the amount of variability or error that occurs in a submaximal isometric force matching task (Kouzaki & Shinohara, 2010). Previous investigations have used both continuous and dynamic isometric force matching tasks to explore the motor control of the lower

extremities(Carville, Perry, Rutherford, Smith, & Newham, 2007; Christou & Carlton, 2001, 2002; Seynnes, et al., 2005). During a continuous isometric task, subjects attempt to generate and sustain a force that matches astatic targetforce value, while for a dynamic isometric task subjects attempt to ramp up and down their isometric force production to match a target force that often has a parabolic shape. While it is normal for a force trajectory to display a small amount of variability or error in its pattern, an increased amount of error is thought to reflect an inaccurate control of the muscular force production. Additionally, it is common for a more dynamic isometric motor task to display a higher amount of variability or error than a continuous isometric contraction. This has been speculated to be due to the higher rate of force production or that the motor command must be constantly alterededduring a dynamic motor task(Christou & Carlton, 2001).

Prior investigations have shown that a greater amount of variability in a submaximal continuous isometric contraction performed with the ankle plantarflexors is related to decreases instanding postural stability(Kouzaki & Shinohara, 2010; Mello, Magalhaes, & Kohn, 2013). Additionally, in our previous investigation, we displayed that a heightened amount of variability in the continuous isometric ankle plantarflexorforce productionwas related withthe degree of upright postural balance impairments seen in individuals with MS(Davies, et al., 2015).Furthermore, a reduction in the amount of variability in the isometric plantarflexion force production seen afterindividuals with MS undergo physical therapywas related to the degree of improvements seen in their standing postural control. However, the reduction in the variability of the continuous isometric plantarflexion force productionwas not related to the improvements in walking

ability. Other prior investigations have also struggled to find a relationship between the variability within a continuous isometric contraction and functional abilities such as walking or climbing stairs (Carville, et al., 2007; Manini, Cook, Ordway, Ploutz-Snyder, & Ploutz-Snyder, 2005; Seynnes, et al., 2005). Potentially, this is due to the dynamic nature of the ankle motor control during these functional tasks. Therefore, the use of a submaximal, dynamic isometric force matching task may be more useful in identifying the motor control deficits of the ankle musculature that may limit walking ability.

The primary purpose of this study was to evaluate the variability of the ankle plantarflexor musculature of individuals with MS while completing a dynamic isometric target matching task. Secondly, we sought to determine whether the amount of variability or errors in the dynamic ankle plantarflexion force production is related to the alterations in the gait patterns that typically occur with MS. Our overarching hypothesis was that individuals with MS would have more errors in their dynamic ankle isometric force production, and that these errors would be directly related to the mobility impairments of individuals with MS.

2.0 Methods

Fifteen individuals with either relapsing-remitting or secondary progressive MS (Mean Age: 53.1 ± 7.6 years; 10 female; EDSS: 4.4 ± 1.0 ; see Table 1 for subject characteristics) and 15 healthy, age and gender matched adults (Mean Age: 53.5 ± 7.4 years; 10 female) participated in this research study. All experimental procedures were reviewed and approved by the University of Nebraska Medical Center Institutional Review Board. Additionally, all subjects provided written informed consent before

participating in the experimental procedures. All experimental procedures were performed barefoot by the subjects without the use of any assistive devices (i.e., canes, ankle-foot orthoses, wheeled walkers).

INSERT TABLE 1 ABOUT HERE

2.1 Motion Analysis of Gait

An eight camera three-dimensional motion capture system (120 Hz; Vicon, Centennial, CO, USA) was used to track a modified Helen Hayes reflective marker set that was placed bilaterally on the lower extremities of each subject. A standing calibration with a knee-alignment device was captured at the beginning of the data collection for each subject in order to ensure that the markers were correctly positioned. Subjects were instructed to walk at their self-selected preferred pace along a pathway instrumented with four force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA). All subjects completed a sufficient number of walking trials in order to acquire at least three trials with consecutive foot contacts where each foot was positioned completely within the boundaries of separate force plates. Walking trials were completed at each subject's own pace and sufficient rest was provided as needed. The Vicon Plug-In Gait module was utilized to calculate the moments generated by the ankle musculature during walking. These moments were normalized to the body weight for each subject.

The variables of interest from the gait data included the maximum moment generated by the ankle at toe-off of the most affected limb for the subjects with MS or the non-dominant limb for the control group. Additionally, the spatiotemporal kinematics

of gait including step width (m), step length (m), walking velocity (m/s), and cadence (steps/min) were calculated from the motion capture data. The data from the respective trials were averaged for the final analyses.

2.2 Dynamic Isometric Ankle Force Control

Dynamic isometric control of the ankle plantarflexors was interrogated using a plantarflexion task where the subjects were required to exert the appropriate amount of isometric force to accurately match a target force that had a sine wave pattern. The MS subjects used their most affected limb and the control subjects used their non-dominant limb for the target matching task. Participants sat on the chair of an isokinetic dynamometer (Biodex, Inc., Shirley, NY) with the backrest angle at 90°. The knee of the subject was fully extended and the ankle was in a neutral position with the subject's foot strapped onto a metal foot plate. Two maximal isometric voluntary contractions were completed, and the highest maximal voluntary torque (MVT) was used to calculate a 20% MVT target force value. The MVT was normalized to each subject's body weight and included in the final analyses.

The sine wave was generated using a custom LabView (National Instruments Inc., Austin, TX, USA) program which employed the use of the Simulate Signal Express VI. The amplitude of the sine wave that each subject was required to follow was set at the 20% MVT value calculated for each subject. The period of the sine wave for the Slow Trials was 35 seconds, while the period for the Fast Trials was 15 seconds. The period of the respective sine waves were selected based on what has been used in previous investigations and our prior pilot testing that was directed at discerning if the respective

periods of the sine waves were achievable(Christou & Carlton, 2001; Davies, et al., 2015; Kouzaki & Shinohara, 2010; Manini, et al., 2005). Constant visual feedback for all trials was provided to the subjects via a computer screen ~1 m in front of them. The program displayed the target as a hollow, green box which moved up and down according to the pattern of the generated sine wave. Additionally, the program provided subjects with feedback about the actual force being produced in real time, which was represented by a solid, red circle (Figure 1). Subjects were instructed to follow the target in such a way to place the red circle inside the hollow green target box as best as they could throughout the entire sine wave motion. All subjects completed three trials of the target matching task for both the Slow Trials and the Fast Trials, for a total of six trials. The order of the trials was randomized between subjects.

INSERT FIGURE 1 ABOUT HERE

The torque output was filtered using a fourth order Butterworth filter with a 25 Hz cutoff. All target-matching data was normalized to each subject's 20% MVT in order to allow for comparison across subjects. The data from the three separate trials for each trial type (Slow Trial or Fast Trial) was averaged together for the final analyses. The root mean square (RMS) was calculated on each trial using the following equation:

$$\text{Equation 1: } RMS = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - t_i)^2}$$

where N is the number of data points in the time series, t_i is the target force, and x_i is the torque sample. The RMS allows for the interrogation of the amount of error in the torque generation of each trial.

2.3 Statistical Analyses

All statistical analyses were performed using IBM SPSS Statistics 22 statistical software (IBM Corp., Armonk, NY, USA). A mixed two-way repeated measures ANOVA (Group $\times$ Trial Type) was used to compare the differences in the RMS between the groups (MS Group vs Control Group) and trial types (Slow Trials vs Fast Trials). Independent samples t tests were used to interrogate the differences between the two groups for the spatiotemporal kinematics, the maximal ankle moment generated at toe-off during gait, and the normalized MVT. Additionally, Spearman rank order correlations were calculated between the RMS, MVT, and all gait variables to determine if the amount of error in the dynamic isometric torque control of the ankle plantarflexors was related to the gait characteristics and muscle strength. An alpha level of 0.05 was used to interrogate all data for significance. The data is reported as the mean $\pm$ standard error of the mean (SEM).

3.0 Results

All 30 subjects completed each portion of the data collection. However, one subject from each group was excluded from the final analyses due to not having evaluable data for all measures.

INSERT FIGURE 2 ABOUT HERE

3.1 Gait Variables

The group with MS displayed shorter step lengths ($t(26)=-3.74$, $p=0.001$; Figure 2A), slower cadences ($t(26)=3.00$, $p=0.006$; Figure 2B), and slower walking velocities ($t(26)=-7.70$, $p<0.001$; Figure 2C) than the healthy adult group. There were no differences in the step widths between groups (MS: 0.18 ± 0.01 ; Controls: 0.17 ± 0.01 ; $t(26)=0.35$, $p>0.05$). Additionally, subjects with MS had a lower maximal ankle joint moment at toe-off ($t(26)=-2.54$, $p=0.017$; Figure 2D) than the healthy adults during gait.

INSERT FIGURE 3 ABOUT HERE

3.2 Dynamic Isometric Ankle Force Control

The group with MS had a significantly lower normalized MVT than the healthy adult group ($t(26)=2.62$, $p=0.007$; Figure 4A). This indicates that our subjects with MS were significantly weaker than the healthy adults, as one would expect. There was a significant Trial Type main effect ($F(1,26)=21.999$, $p<0.001$; Figure 4B) for the RMS, with the Fast Trials having a higher RMS than the Slow Trials. Hence, indicating that more errors occurred when the isometric force was generated at a faster rate by the ankle. Additionally, there was a significant Group main effect ($F(1,26)=6.013$, $p=0.021$; Figure 4C) for the RMS with the subjects with MS having a higher RMS than the control group. This main effect displayed that there were more errors overall in the isometric ankle force control of the individuals with MS than in the healthy adults. There was no significant Group by Trial Type interaction ($F(1,26)=0.004$, $p>0.05$).

3.3 Root Mean Square Correlations

All correlations between the RMS of the Slow and Fast Trials, the gait variables, and normalized isometric MVT are reported in Table 2. These reported correlations are for both groups combined. Exploration of the data separated by group indicated that there were no significant correlations between any variables for the individual groups. The RMS of the Fast Trials was negatively correlated to the maximal ankle joint moment at toe-off during walking ($p = 0.012$), which indicated that greater errors during the Fast Trials are associated with lower maximal moments generated by the ankle. Both the RMS of the Slow and Fast Trials were negatively correlated to the step length during walking (RMS Slow: $p = 0.002$; RMS Fast: $p = .011$). This indicated that greater errors during either trial type were associated with shorter step lengths. Additionally, the RMS of the Slow Trials was negatively correlated with walking velocity ($p = 0.004$), which indicated that a greater amount of error in the Slow Trials was associated with slower walking speeds.

INSERT TABLE 2 ABOUT HERE

3.4 Maximal Voluntary Torque Correlations

There was a positive correlation between the normalized MVT and the maximal ankle moment at toe-off during walking ($r = 0.579$, $p = 0.001$). This correlation indicated that individuals that generated a weaker torque also tended to have lower moments generated by the ankle during walking. The RMS of both the Slow and Fast Trials were negatively correlated with the normalized MVT (RMS Slow Trials: $p = 0.005$; RMS Fast Trials: $p < 0.001$). These correlations indicated that individuals

that had a weaker maximal torque also tended to have greater errors in the dynamic ankle isometric target matching tasks.

4.0 Discussion

Our study sought to quantify the motor control of the ankle plantarflexor musculature of individuals with MS during a dynamic isometric force matching task. Additionally, our study explored the relationship between the motor control deficits in the ankle plantarflexor force production and the walking alterations that occur with MS. The outcomes from our study indicated that individuals with MS had greater errors in the dynamic isometric ankle force production. Not surprisingly, our subjects with MS also walked with altered spatiotemporal kinematics, and had a reduced maximal ankle moment at toe-off during walking than the healthy control group. In addition, the subjects with MS also had weaker ankle plantarflexor strength than the healthy adult group as demonstrated by the lower normalized isometric MVT generated by the subjects with MS. The increase in error during the dynamic isometric ankle force matching task was related to the decreases in step length and walking speed, decreases in maximal moments at the ankle during the toe-off phase of walking, and the reduced strength of the ankle plantarflexor musculature. Altogether, these outcomes suggest that the walking limitations of individuals with MS may be partly due to errors in the control of the ankle plantarflexors during dynamic motor tasks such as walking.

There was a greater amount of variability or errors in the ankle isometric force production when completing the Fast Trials than the Slow Trials. This outcome was not surprising because previous investigations have found higher amounts of variability

1 when the parameters of the motor task are altered to increase the speed and/or
2 complexity of the task(Christou & Carlton, 2001; Van Cutsem, Duchateau, & Hainaut,
3 1998; Wessberg & Kakuda, 1999). Systematic changes in variabilityalso occur with an
4 increased rate of force production or a higher movement velocity;this increase in
5 variability may be due to altered motor unit recruitment or more variable motor unit
6 discharge rates(Newell, Carlton, Kim, & Chung, 1993).Potentially, the differences seen
7 in this investigation may be related to the rate of the change in the isometric force
8 production between slow and fast conditions. Alternatively, we suggest that the
9 differences may be relatedto the ability to utilize feedback during the motor task to make
10 proper adjustments to minimize the amount of error in the motor performance. During a
11 slower motor task, one is able to utilize the proprioceptive and visual feedback while
12 there may not be sufficient time to process this information during a faster motor task.

13 The individuals with MS in our study displayed more errors in their ankle
14 plantarflexionforce generation than our healthy adult group. This results implies that the
15 control of the precision of the dynamic force production of the ankle plantarflexors in
16 individuals with MS is likely aberrant. Previous electroencephalography investigations
17 have suggested that the damage upon the central nervous system caused by MS may
18 impact the cortical activations associated with the production of motor actions(Leocani,
19 et al., 2001; Leocani, et al., 2005).Additionally, transcranial magnetic stimulation studies
20 have shown slowed transmission of the motor command along the corticospinal tract,
21 which would result in altered movement patterns(Gagliardo, et al., 2007; Kale, Agaoglu,
22 Onder, & Tanik, 2009). Moreover, individuals with MS have slowed somatosensory
23 conduction which may also influence the rate at which information can be received and

1 processed for proper execution of the motor task(Cameron, et al., 2008). Altogether
2 these prior results suggest that the increased amount of error in the dynamic isometric
3 force productionof our subjects with MS may reflect the damage within the corticospinal
4 tracts and/or the sensorimotor cortices.

5 The individuals with MS had significantly weaker plantarflexors than the age-
6 matched controls, which is aligned with what has been reported in prior
7 studies(Armstrong, et al., 1983; Kent-Braun, et al., 1997; Lambert, et al., 2001;
8 Ponichtera, et al., 1992; Rice, Vollmer, & Bigland-Ritchie, 1992; Steens, et al.,
9 2012).However, our results are novel because they show that the subjects with weaker
10 muscles also tended to have more errors in their dynamic ankle force production.
11 Previous investigations have found that weaker individuals of any age have higher
12 amounts of variability in the force generation patterns of their upper extremities(Sosnoff
13 & Newell, 2006). It has also been previously shown that weaker muscles typically have
14 a morevariable motor output due to the higher motor unit firing rates and fewer active
15 motor units(Hamilton, Jones, & Wolpert, 2004). Potentially, the heightened errors seen
16 in the dynamic force production of the individuals with MS may be related to the
17 decreased and more variable motor unit discharge rates as well as incomplete motor
18 unit recruitment(Dorfman, Howard, & McGill, 1989; Kent-Braun, et al., 1997; Rice, et al.,
19 1992).Previous investigations suggest that resistance training programs can decrease
20 the motor unit firing rate variability and influence the motor unit synchronization, thus
21 resulting in better motor control(Kornatz, Christou, & Enoka, 2005; Semmler &
22 Nordstrom, 1998). Possibly,a progressive resistance training mayimprove the motor
23 control of the ankle muscular force production.

1 The subjects from our study walked with slower and more reduced
2 spatiotemporal kinematics than what has been previously reported for individuals with
3 MS suggesting that our subjects potentially had more disability than those in previous
4 investigations(Huisinga, et al., 2013; Kelleher, et al., 2010; Martin, et al., 2006).
5 Additionally, this notion is supported by the lower peak ankle moment of the MS
6 subjects in our study than those found in previous investigations(Huisinga, et al., 2013).
7 Previous investigations have suggested that the reduced peak ankle moment at the
8 ankle is a predictor of reduced step lengths and walking speeds in individuals with
9 MS(Huisinga, et al., 2013).The neuromuscular alterations of the ankle musculature of
10 individuals with MS such as spasticity, decreased muscle strength, and impaired
11 proprioception have been proposed as contributing factors to these gait
12 limitations(Sosnoff, et al., 2011; Wagner, et al., 2014). In our study, the reduced peak
13 ankle moment generation during walking was related to weaker MVT. These results
14 suggest that the decreased muscle strength in individuals with MS may be a
15 contributing factor to the reduced maximal ankle torque generated during walking and
16 indirectly the decreased spatiotemporal kinematics.

17 The increased amount of error in the dynamic ankle isometric motor task was
18 also associated with the reductions in the spatiotemporal gait kinematics. Specifically,
19 the error was related to the reduced step length and slower walking velocity. In addition
20 to reduced spatiotemporal kinematics, the amount of error in the dynamic isometric
21 ankle motor task was also related to reduced maximal moments generated by the ankle
22 during gait. These results suggest that the deficits in the gait patterns of individuals with
23 MS may not be solely due to the neuromuscular alterations such as muscle weakness.

1 Rather, these outcomes suggest that the errors in the control of the ankle during gait
2 may contribute to a higher amount of internal perturbations in the gait patterns in
3 individuals with MS. This could potentially be why individuals with MS have higher
4 amounts of variability in their spatiotemporal kinematics of gait(Crenshaw, Royer,
5 Richards, & Hudson, 2006; Socie, Motl, Pula, Sandroff, & Sosnoff, 2013).

6 Previous investigations quantifying the relationship between continuous isometric
7 contractions of the lower extremities and functional tasks in healthy populations have
8 been inconclusive(Carville, et al., 2007; Manini, et al., 2005; Seynnes, et al., 2005).
9 While Seynnes et al.(Seynnes, et al., 2005) discovered a relationship between brief,
10 stressful functional tasks, such as chair rising or stair climbing, and steadiness during a
11 continuous isometric contraction with the knee,Manini et al.(Manini, et al., 2005) failed
12 to find such a relationship. Additionally, results from our recent therapeutic investigation
13 suggested that improvements in continuous isometric motor control of the ankle
14 musculature were not related to improvements in gait parameters in individuals with
15 MS(Davies, et al., 2015). Our current results suggest that these inconclusive results
16 may be due to the use of a continuous motor task rather than a dynamic motor task to
17 quantify the motor control of the ankle plantarflexors.

18 Previous investigations have shown that therapeutic exercise programs of
19 various types can promote improvements in the mobility of individuals with MS. It has
20 been shown that aerobic exercise can result in moderate improvements in the walking
21 speed and endurance of individuals with MS (Newman, et al., 2007; van den Berg, et
22 al., 2006). Additionally, rehabilitation protocols targeting the postural control of
23 individuals with MS have produced improvements in walking capacity (Cattaneo,

Jonsdottir, Zocchi, & Regola, 2007; Hebert, Corboy, Manago, & Schenkman, 2011). Resistance training programs targeting the lower extremities of individuals with MS have also promoted improvements in the gait kinematics of these individuals (Gutierrez, et al., 2005; White, et al., 2004). Moreover, clinically relevant improvements in the mobility of individuals with MS have also occurred after group fitness classes or combined strength and aerobic training programs (Jackson, Edginton-Bigelow, Cooper, & Merriman, 2012; Motl, et al., 2012). Despite the promising outcomes of these previous studies, the expected outcomes across these studies are somewhat blurred with some individuals demonstrating large improvements, whereas other individuals are classified as nonresponders. Based on the outcomes from the current study, we suspect that the degree of the improvements in the gait of individuals with MS following therapeutic protocols may be related to the amount of change that occurs in the motor control of the ankle musculature. Future investigations should explore whether improved dynamic motor control of the ankle joint is related to improvements in the mobility of individuals with MS following such interventions.

4.1 Limitations

A limitation of this study was that we did not evaluate spasticity or the level of sensory impairment such as proprioception. It has been suggested that the compensatory gait strategies employed by individuals with MS may be due to spasticity or impaired proprioception (Socie & Sosnoff, 2013; Wagner, et al., 2014). Since this investigation did not evaluate these characteristics, we are unable to comment on the influence of these variables on the motor control of the ankle or spatiotemporal kinematics of gait in individuals with MS. Our study was also limited by the wide range

of ability level of the subjects with MS. However, this was selected in order to attempt to understand the influence of MS as a disease on the ankle motor control and gait patterns. Also, the sample sizes utilized in the current study were small, which limited our ability to identify the smaller differences seen in some of the measured variables. Finally, the study is limited in its application due to the fact that the relationships between the ankle motor control and gait or MVT were evaluated using the two groups combined rather than separated groups. Therefore, based on the current data, we are unable to draw definite conclusions about the relationships between these variables for each group separately. Future investigations should take these limitations into account and build upon the findings of the current investigation.

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1 **Figure Captions**

2 **Figure 1: A)** The experimental set-up for the dynamic isometric ankle force matching
3 task. **B)**A representative force trajectory graph for an individual with MS during a Slow
4 Trial. **C)**A representative force trajectory graph for a healthy, control subject during a
5 Slow Trial. Inspection of panels B and C clearly show that the individual with MS had a
6 greater amount of error in their dynamic ankle isometric force production than the
7 healthy control.

8 **Figure 2:** The between group differences for **A)** step length, **B)** cadence, **C)** walking
9 velocity, and maximum ankle moment at toe-off during walking. These results show that
10 the individuals with MS walked slower and had a reduced step length, slower cadence
11 and generated a lower moment by the ankle at toe-off. * indicates $p < 0.05$.

12 **Figure 3: A)** The between group differences for the normalized maximal voluntary
13 torque. This graph shows that the group with MS had weaker ankle plantarflexors than
14 the healthy controls. **B)**The Trial Type Main Effect for the normalized RMS of the torque
15 during the dynamic isometric force matching task. This graph shows that there were
16 more errors generated by both groups during the Fast Trials compared with the Slow.
17 **C)** The Group Main Effect for the normalized RMS of the torque during the dynamic
18 isometric force matching task. This graph shows that the group with MS overall had
19 greater errors in the dynamic isometric ankle force production for both the Slow and
20 Fast Trials compared with the healthy controls. * indicates $p < 0.05$.

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A.

Normalized Isometric
Maximal Voluntary
Torque(Nm/kg)

B.

Normalized Root Mean
Square

C.

Normalized Root Mean Square

Table 2: Spearman rho rank order correlations between the RMS, the gait variables, and normalized MVT.

	Walking Velocity	Step Length	Step Width	Cadence	Maximal Ankle Moment	Normalized Isometric MVT
RMS Slow	-0.523*	-0.553*	-0.028	-0.262	-0.235	-0.518*
RMS Fast	-0.320	-0.471*	-0.106	0.026	-0.469*	-0.624*

* indicates $p < 0.05$.

Table 1: Subject Demographics for the MS Group

Subject	Age	Gender	MS Diagnosis	Years with MS	EDSS	Assistive Device for Community Ambulation
1	57	F	RR	19	4.0	Cane
2	48	M	SP	12	5.5	Cane
3	50	F	RR	12	3.5	None
4	57	F	RR	12	4.0	None
5	55	M	SP	4	4.5	None
6	53	M	RR	15	4.0	None
7	58	F	RR	33	6.0	Cane/Walker
8	36	F	SP	14	6.5	Walker
9	57	M	RR	16	4.0	None
10	72	F	RR	34	4.0	Cane
11	53	F	RR	20	5.0	Walker
12	50	F	RR	23	3.0	None
13	53	M	RR	14	3.0	None
14	48	F	RR	20	4.0	Cane
15	50	F	RR	15	4.5	Cane

Abbreviations. MS, multiple sclerosis; RR, relapsing-remitting multiple sclerosis; SP, secondary progressive multiple sclerosis