4-2017

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Recommended Citation

Migliore, Cody, "Comparison of the Kinematics and Muscle Responses During Obstacle Avoidance in People with Stroke" (2017). *Honors Theses*. 1022.
https://repository.lsu.edu/honors_etd/1022

Comparison of the Kinematics and Muscle Responses During Obstacle Avoidance in People with Stroke

by

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Undergraduate honors thesis under the direction of

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Submitted to the LSU Roger Hadfield Ogden Honors College in partial fulfillment of
the Upper Division Honors Program.

April 2017

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Baton Rouge, Louisiana

Introduction

In the United States, stroke is the fifth leading cause of death and a major cause of adult disability (Kochanek et al. 2013), affecting people physically, cognitively, visually, and verbally. Stroke can lead to various impairments in motor functions such as paresis, spasticity, and impaired coordination, which can disturb gait. Post stroke, simple tasks such as walking and obstacle clearance increase in difficulty, such that people with stroke experience difficulty in adapting their gait to changes in the environment (Van Swigchem, van Duijnhoven, den Boer, Geurts, & Weerdesteyn, 2013). Due to this loss of proficiency, the risk of falls and injuries generally increases in people with stroke; therefore, to regain strength and better understand their newfound limitations, people with stroke often require multiple types of therapy such as physical, occupational, and speech therapy.

Researchers show that locomotion characteristics of healthy individuals and people with stroke differ. During unobstructed walking, the gait of healthy individuals in comparison to those with stroke primarily reveals increases in step lengths and step frequencies and lower step-to-step variabilities; and to step over an obstacle, healthy individuals normally utilize a knee flexion strategy (McFayden and Winter, 1991). Decreased step lengths, decreased step frequencies, and increased step-to-step variabilities occur after a stroke, which all increase the difficulty of walking (Den Otter, Guerts, de Haart, Mulder, & Duysens, 2005). The increased step-to-step variabilities are a critical deficit that occurs in people with stroke, affecting their postural stability, weight bearing strength, and body transfer capabilities (Song and Ryu, 2016). While crossing an obstacle, people with stroke resort to increased hip elevation, abduction, circumduction, and ankle dorsiflexion to compensate for a decrease in knee and hip flexion (MacLellan, Richards, Fung, & McFayden, 2015). Other than the general gait changes that occur in people with stroke, further kinematic analyses reveal an increase in obstacle crossing times along with a decrease in post-obstacle distances (Said et al., 2005).

Kinetic analyses reveal that people with stroke tend to decrease peak ankle flexor moments and increase knee peak flexor moments during swing phase in the non-paretic limb as obstacle height increases (MacLellan et al., 2015). This study also indicated that the peak hip flexor moment in the non-paretic limb was greater during obstacle clearance than walking. In the paretic limb, the peak knee flexor moment in swing was larger during obstacle clearance than walking; but no significant changes were observed for the peak ankle and hip flexor moments. In a comparison across trials on the paretic limb, during walking, a higher peak knee flexor moment occurred; and for obstacle clearance, an increased peak hip flexor moment occurred. With this information, a general observation can be concluded that people with stroke must utilize a hip flexor strategy to step over obstacles as opposed to the knee flexor strategy used by healthy individuals (McFayden and Winter, 1991).

Although several studies explore the kinematics and kinetics in people with stroke, relatively few studies have examined muscle activation patterns during obstacle clearance. Examination of electromyography (EMG) allows for researchers to explore the differences in muscle activations during locomotion. Prior studies examining muscle activation during obstacle avoidance in people with stroke involved the sudden dropping of an object in front of them on a treadmill. In the healthy individuals, the biceps femoris (BF) on the crossing leg and the rectus femoris (RF) on the stance leg were the first muscles to respond to avoid the obstacle; and these two muscles also demonstrated the highest rates of occurrence and largest amplitudes (Van Swigchem et al., 2013). However, in people with stroke, EMG responses were less consistent and delayed. During obstacle avoidance, the onsets of BF in the crossing leg, RF in the stance leg, and gluteus maximus (GM) in the crossing leg were delayed in comparison to other muscles. Initial response amplitudes in BF in the crossing leg and RF in the stance leg were lower as well (Van Swigchem et al., 2013). Different step strategies needed to be used by the participants to clear the obstacle depending on the time of the gait cycle the object was dropped. The implementation of a treadmill, though, poses a problem: as daily walking cannot be accurately simulated, allowing response time to become a factor. Dropping an object on a treadmill forces the participant to react to the obstacle. In fact, muscle responses to an unexpected event differ from one that is expected (Nieuwenhuijzen, Schillings, Van Galen, & Duysens, 2000). To eliminate the modulation of gait due to reaction time, this study utilizes a stationary walkway with a fixed obstacle. Furthermore, both limbs will be required to clear the obstacle in the present study rather than merely the affected limb as in the treadmill study.

In addition to the research of kinematics, kinetics, and EMG, studies using rehabilitative strategies such as body weight supported treadmill training (Visintin, Barbeau, Korner-Bitensky, & Mayo, 1998), multidirectional step training (Park, Choi, & Kim, 2016), and proprioceptive neuromuscular facilitation (Park and Moon, 2016) have been conducted in the past to identify efficient strategies to recover people post-stroke. Although these studies may have shown ways to increase balance, weight shifting, and trunk stability, none of them demonstrated improving obstacle avoidance as a rehabilitative strategy, which this study will observe since the ability to step over obstacles is crucial in reducing the risk of falls in people with stroke.

The purpose of this research is to compare the muscle activations in the leading limb of a healthy individual and the leading paretic and non-paretic limbs of people with stroke in two different situations: walking without obstruction, and when crossing an obstacle. In this case study, the healthy participant will be compared to two individuals with stroke, one with a cerebellar stroke and the other with a cortical stroke. With these participants, a comparison can be made amongst people with differing symptoms due to stroke as a cerebellar stroke can affect the coordination of these joints during obstacle clearance (Morton, Dordevic, & Bastian, 2004), while a cortical stroke results in delayed and hindered signaling from the cortex causing reduced motor functions. This research may be able to provide physical therapists with valuable information about the muscles used during obstacle clearance in people with stroke, allowing them to pinpoint their rehabilitation more efficiently to better prevent post-stroke falls. By comparing the ratios between the non-obstructed and obstructed trials in each limb using normalized EMG values, it is hypothesized that when the non-paretic limb leads, the knee flexors, the semitendinosus (ST), will increase activation; but when the paretic limb leads, the RF, a hip flexor, will need to activate more to compensate for lost flexion in the knee to allow the limb to cross, as seen in the study conducted by Van Swigchem et al. (2013).

Methods

Three male participants were recruited for this study: a healthy individual (age: 59 yrs, weight: 84.0 kg, height: 1.75 m), a person with a cortical stroke (age: 62.7 yrs, weight: 101.0 kg, height: 1.94 m, side of stroke: right), and a person with cerebellar stroke (age: 64.5 yrs, weight: 64.4 kg, height: 1.67 m, side of stroke: right). Participants were required to walk without any assistance or aid for at least 10 meters, have no musculoskeletal or neurological disorders (aside from a previous stroke), and possess the ability to follow instructions. Informed consent was obtained prior to the experiment and the study was approved by the Institutional Review Board at Louisiana State University.

The experimental protocol included two different tasks: unobstructed walking and obstacle clearance. These tasks were completed on a wooden, custom-made, and fixed walkway approximately 10 meters in length. During the trials of unobstructed walking, the participants were asked to walk comfortably across the walkway; and for obstacle clearance trials, the participants were asked to step over a 0.1 m obstacle placed in middle of the walkway while walking at steady state. To ensure the participant reached a steady state of walking, each participant began their trials at a minimum of two strides before reaching the obstacle. Each task included 10 randomized trials for the participants to complete, with five of the trials performed with the paretic limb leading and the other five performed with the non-paretic limb leading. To ensure randomization in the trials, the participants were not given instructions on which foot to use to step over the obstacle, allowing them to choose the foot to use on their own. To have participants step over the obstacle with either their paretic or non-paretic limbs, their starting position was manipulated. In an attempt to control for the difference in gait speed between healthy individuals and people with stroke, the healthy participant was instructed to walk at a comfortable pace for one condition and a slower pace for the other.

Three-dimensional kinematic data were recorded using a 4-sensor Codamotion CX1 system (Charnwood Dynamics Ltd., Rothley, UK) at 100 Hz. Infrared-emitting markers were placed on anatomical landmarks bilaterally to record the changes in joint angles and positions during the trials. Marker data were filtered offline using a zero-lag, second-order, Butterworth filter with a low-pass cutoff of 7 Hz. Markers were placed on the greater trochanter, the lateral head of the fibula, the lateral malleolus, the first metatarsal, the fifth metatarsal, and the calcaneus. Heel contacts were identified by finding peaks and bases in the vertical position of the calcaneus marker. The identified heel contacts were used to time-normalize the marker trajectories to 200 points for inter-stride averaging. To determine the gait speed for each stride for both conditions, the horizontal distance the heel traveled across the stride was divided by the time taken to complete the stride. For each condition and trial, data from five strides were attempted to be obtained; but due to missing data, only three or four strides could be analyzed for some of the trials. Average joint angle trajectories for the hip, knee, and ankle and the vertical toe height were calculated across the strides for each trial. The vertical toe height was determined by the change in the vertical position of the marker on the first metatarsal during the swing phase of the gait cycle. Furthermore, the ranges of these joint angles were determined by calculating the difference between the maximum and minimum values of each joint angle for each stride.

Electromyography data were recorded using a 32-channel MA-300 system (Motion Lab Systems Inc., Baton Rouge, LA) and sampled at 2000 Hz. The placement of electrodes was determined using Surface EMG Non-Invasive Assessment of Muscles (SENIAM) guidelines or by palpation. The muscles examined in this study included the gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), semitendinosus (ST), tibialis anterior (TA), and gastrocnemius (GAS). EMG data were filtered offline using a zero-lag, second-order Butterworth filter. Data were initially high-pass filtered at 30 Hz to remove low frequency noise, then rectified and filtered a second time with a 10 Hz low pass filter to obtain a smoothed envelope. Similar to the kinematic data, EMG data were time-normalized to 200 points for inter-stride averaging. Muscle activation trajectories were normalized relative to the peak value during unobstructed walking in each muscle and participant for all trials and expressed as a ratio relative to the peak. Additionally, the mean muscle activity for each muscle was calculated by averaging all of the muscle activation trajectories for each stride in all of the trials. The use of mean muscle activity will allow for a demonstration of the overall changes in muscle activity that occur across the entire gait cycle for each stride.

Results

Kinematics

In Figure 1, the average gait speeds are illustrated for each participant on their non-paretic and paretic limbs during level walking and obstacle clearance. During the level walking trials, the participant with cerebellar stroke demonstrated higher average gait speeds than both the healthy participant and the participant with cortical stroke. The speed for the healthy participant during the slow-paced condition was similar to the speed on both limbs of the participant who sustained the cortical stroke for both level walking and obstacle clearance. Since this gait speed was similar between these conditions, the joint and muscle activation changes that occurred in the participant with cortical stroke during the trials were not due to gait speed. Across limbs, the participants with stroke revealed similar gait speeds on each lower limb for both level walking and obstacle clearance. Lastly, apart from the healthy individual's normal-paced condition, all individual gait speeds decreased when going from level walking to obstacle clearance.

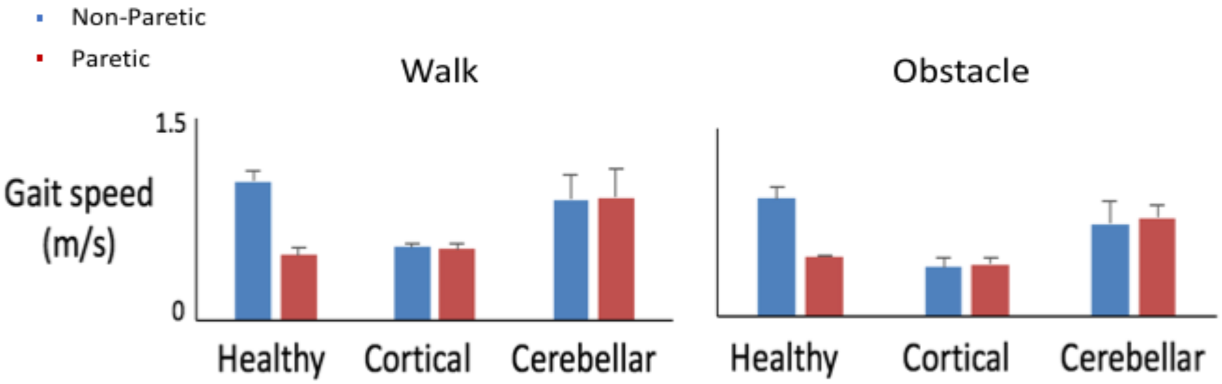

Figure 1. Average gait speeds for the leading limbs during level walking and obstacle clearance. Bar graphs indicating average gait speeds +1 standard deviation (SD) for five strides, respectively, for the non-paretic (blue) and paretic (red) limbs are shown. Gait speed was measured in meters per second, and higher values indicate faster average speeds while lower values indicate slower average speeds.

Average joint angle trajectories for the three participants during walking and obstacle clearance are shown in Figure 2, while average joint ranges are demonstrated in Figure 3. Positive values for the average joint angle trajectories indicate flexion, while negative values indicate extension. As previously discussed, one of the participants sustained a cerebellar stroke; therefore, the neural connections from the central nervous system to the lower limb may not have been as disrupted as the connections in the individual who sustained a cortical stroke. Since the participant with cerebellar stroke may not have had these disturbed connections, in some instances, his joint angle values and EMG recordings were more similar to the healthy participant than to the participant with cortical stroke.

During obstacle clearance, the participants with stroke tended to reveal a greater hip flexion in comparison to the healthy participant on both limbs. Additionally, the participant with cortical stroke revealed higher hip flexion in his non-paretic limb than his paretic limb, while the participant with cerebellar stroke had similar average trajectory and range hip flexor angles in both limbs. All participants revealed similar knee flexor angles, around 50 degrees, on their non-paretic limbs during the walking trials, but the healthy participant showed a higher knee flexor angle, closer to 100 degrees, for both sides during obstacle clearance. On the other hand, the participants with stroke revealed increased ankle dorsiflexion during both walking and obstacle clearance and increased toe elevations, especially for the paretic limb, reaching over 0.3 m during obstacle clearance. In a comparison across limbs, the paretic limb had higher ankle flexor trajectories and had increased toe elevation to clear the obstacle; but the non-paretic limb showed increased flexor trajectories for the hip and knee during obstacle clearance.

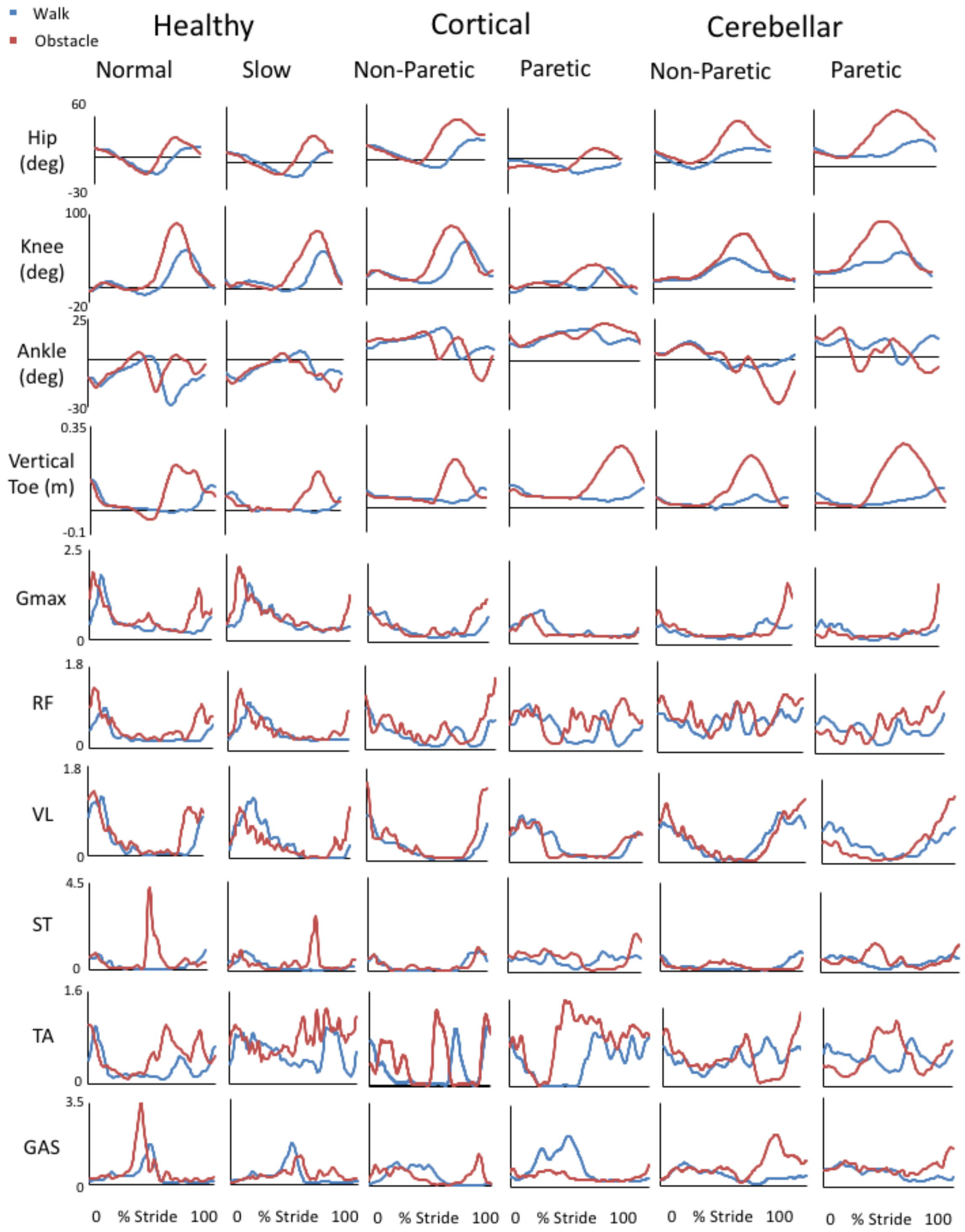

Figure 2. Average joint angle trajectories and muscle activations for the leading limbs. 0 and 100% indicate the beginning and end of the stride cycle. The average kinematics and EMG over five strides, respectively, are shown for level walking (blue) and clearing an obstacle (red). Positive and negative values for the kinematic graphs indicate flexion and extension while the positive values for the EMG graphs indicate values normalized as ratios of the peak value calculated during unobstructed walking for each muscle.

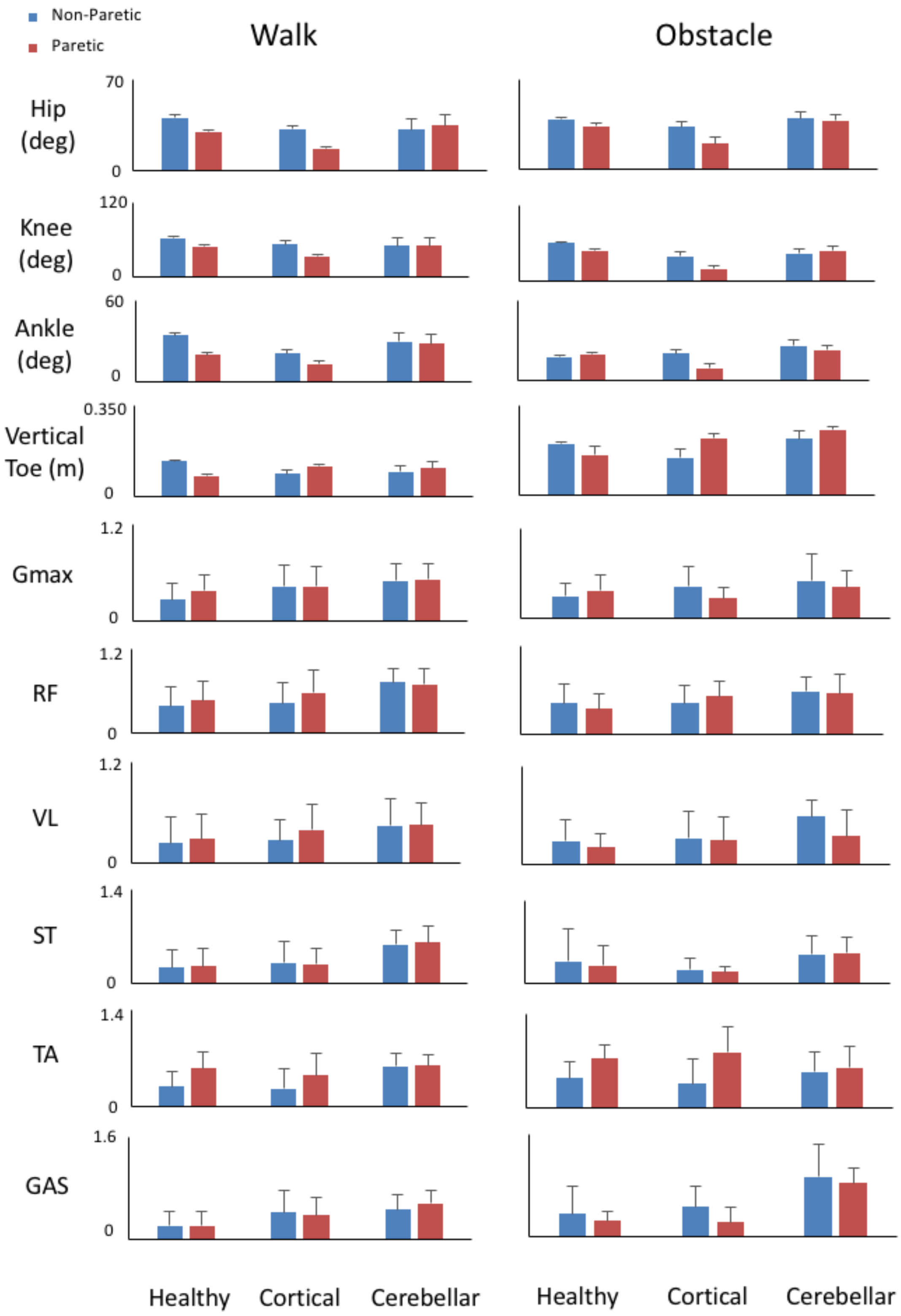

Figure 3. The average range values for the kinematics and average EMG recordings in the non-paretic (blue) and paretic (red) limbs. Bar graphs indicating average range joint angles and mean EMG ratios +1 standard deviation (SD) during level walking and obstacle clearance are shown. Higher positive values indicate greater joint angles in the kinematics and larger normalized muscle activation in the EMG.

Muscle Activation Patterns

The average normalized muscle trajectories from the EMG recordings for the six muscles are illustrated in Figure 2, while Figure 3 demonstrates the mean muscle activities for each muscle during walking and obstacle clearance for all participants. For both conditions, the healthy participant had increased muscle activation trajectories in the GM at the beginning of the gait cycle for walking and obstacle clearance trials, yet the participant with cerebellar stroke had a higher GM activation in both limbs at the end of the obstacle clearance trial than both other participants. In the participants with stroke, the RF and VL were typically more active in the beginning and end of their gait cycles for both walking and obstacle clearance in comparison to the healthy individual. The non-paretic limb of both participants with stroke revealed higher peaks and activations for these two muscles as well compared to the paretic limb. For the ST, the healthy individual revealed a maximum ratio over 4.0, compared to the peak ST value in level walking, during normal-paced obstacle clearance and another over 2.5 during slow-paced obstacle clearance, which were significantly higher than the participants with stroke.

The participants with stroke showed relatively similar muscle activations for the ST during both level walking and obstacle clearance and in both limbs. All participants during the walking trials revealed similar muscle activations in the GAS on both sides, but during obstacle crossing, the healthy participant revealed the highest ratio, close to 3.5 times the peak value for level walking, for the GAS while walking at a comfortable pace. Comparing GAS activation during obstacle clearance in the two participants with stroke, the participant with cerebellar stroke demonstrated higher muscle activation. Additionally, both participants with stroke revealed greater GAS activations in the non-paretic limb compared to the paretic limb.

Discussion

The ability to step over an obstacle has been the center of several studies in the attempt to determine the strategies used by people with stroke; however, these studies have mostly focused on the kinematics and kinetics, apart from one study utilizing EMG recordings (Van Swigchem et al., 2013). Although research before this has utilized EMG, the participants walked on a treadmill and the obstacle was released unexpectedly, forcing the participants to react and preventing a true simulation of everyday walking. Since this study used a stationary walkway, the participants were able to anticipate the obstacle as opposed to having to react to one dropped in front of them.

In prior kinematic studies, research supports that people with stroke resort to increased hip elevation, abduction, circumduction, and ankle dorsiflexion to compensate for a decrease in knee and hip flexion (MacLellan et al, 2015). While people with stroke resort to these strategies, healthy individuals simply utilize a knee flexor strategy to step over an obstacle (McFayden and Winter, 1991). Comparable to the study conducted by MacLellan and colleagues (2015), an increase in hip flexion occurred along with a decrease in knee flexion in the participants with stroke during obstacle clearance was identified during the current study. Since knee flexion typically decreases after stroke, people with stroke compensate by using their hip to lift their leg over an obstacle. Additionally, a decrease in ankle dorsiflexion along with an increase in toe clearance over the obstacle occurred, depicting that people with stroke pick their foot up higher than healthy individuals to cross an obstacle. Said et al. (2001) previously showed that people with stroke clear obstacles with a greater height than healthy individuals as a safety adaptation. Since people with stroke generally have decreased dorsiflexor control in their paretic ankle, they want to ensure that they do not come in contact with the obstacle.

The results of the muscle activations in this study can be used to relate to kinetic strategies used during obstacle clearance. In the healthy population, knee flexor moments are the main tactic used to traverse obstacles (McFayden and Winter, 1991). Results from the current study revealed the a much higher peak in the ST, a primary knee flexor, on both sides in the healthy participant during obstacle clearance in comparison to the participants with stroke. This indicates that the knee flexor strategy was utilized the healthy participant, supporting McFadyen and Winter (1991). Although less ST activation in the paretic limb occurred in the participants with stroke during obstacle clearance, an increase in RF, an essential hip flexor, activation was noticed in the paretic limb during obstacle clearance. These findings agree with the past research conducted by MacLellan and colleagues (2015) stating that a decrease in knee flexor moments is coupled with an increase in hip flexor moments during obstacle clearance in people with stroke. Since people with stroke cannot flex their paretic knee efficiently, they must supplement this with hip flexor activation on their paretic limb to lift it over obstacles, which explains the increase in RF activation. Although knee flexion decreases in the paretic limb, this study revealed knee angle trajectories on the non-paretic limb of the participants with stroke that were similar to the healthy individual, which means that the non-paretic limb is able to conserve a knee flexor strategy for obstacle clearance. Additionally, an increase in TA activation during obstacle clearance was observed in the non-paretic limb in this study, which depicts ankle dorsiflexion occurring; however, MacLellan et al. (2015) recognized a decrease in peak ankle flexor moments in the non-paretic limb during obstacle crossing.

In the previous study using EMG (Van Swigchem et al., 2013), both the stance and crossing legs were analyzed while, for this study, only the leading limb muscle activations were observed. Also, in this study, the participants had to clear the obstacle with both limbs; while in the research by Van Swigchem et al. (2013), they only had to step over the obstacle with one foot. Another significant difference between these studies is the use of feedback and feed-forward information. Having to react to an obstacle and acquire information while performing a task clearance would be considered feedback control, which was the method necessary to use in the study by Van Swigchem et al. (2013). Being forced to use feedback control, the participants with stroke struggled to traverse the obstacle in some instances, colliding with it and knocking it over. On the other hand, since the current study allowed participants to visually see the object and anticipate it before performing the task, they were able to utilize feed-forward control, which increased their ability to step over the obstacle and minimized collisions. Van Swigchem and colleagues (2013) determined that the BF was most prevalent in healthy individuals during obstacle clearance, yet this current study analyzed the ST, another knee flexor, instead. Results from the current study identified the ST as activating most during obstacle clearance in healthy participants, observing that healthy participants use a knee flexor strategy to cross obstacles. For the participants with stroke, though, Van Swigchem et al. (2013) found that the GM in the stance leg and the BF in the crossing leg activated most during obstacle clearance but were reduced and delayed in their responses compared to the healthy individuals. In this study, the lead limb on both sides of the participants with stroke revealed increased activations in the RF during obstacle clearance, which agrees with prior studies stating that people with stroke typically utilize a hip flexor strategy to cross obstacles.

The results from this study can allow therapists a better understanding of the muscles needed to activate for obstacle clearance in people with stroke. To supplement successful past rehabilitative strategies, such as BWS treadmill training (Visintin et al., 1998), multidirectional step training (Park et al., 2016), and proprioceptive neuromuscular facilitation strategies (Park and Moon, 2016), the first-hand knowledge of muscle activation will allow for further and more efficient therapeutic approaches to be implemented for the improved prevention of falls.

This study contained several limitations. Only a small number of participants were analyzed, preventing the results from being generalized to a population. Also, since participants were required to have the ability to walk without any aid or assistance for at least 10 meters, the results can only be applied to that population. The participants with stroke did not have strokes that occurred in the same region of the brain, which means that different deficits affect them; therefore, their responses to obstacle clearance would not necessarily be similar. Lastly, gait speed was constantly changing across each stride due to the increased stride variability in people with stroke, which may have altered the data across strides.

In conclusion, as past studies have revealed, this study showed that healthy individuals utilize knee flexion for obstacle avoidance (McFayden and Winter, 1991), supported by the ST activation in those trials. In the participants with stroke, an increase in hip flexion occurred during obstacle avoidance, revealed by the larger average hip trajectories and ranges as well as an increased RF activation, an essential hip flexor. Additionally, the participants with stroke revealed higher toe clearances, most likely due to the increased activation in the TA, an ankle dorsiflexor. These results agree with the findings of past studies and further enforce the most well-known methods utilized by people with stroke to traverse obstacles.

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