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Adaptation of Human Locomotion and Unilateral Limb Loading During Different Inclination Treadmill Walking

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ADAPTATION OF HUMAN LOCOMOTION AND UNILATERAL LIMB LOADING DURING DIFFERENT INCLINATION TREADMILL WALKING

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ABSTRACT

ADAPTATION OF HUMAN LOCOMOTION AND UNILATERAL LIMB LOADING DURING DIFFERENT INCLINATION TREADMILL WALKING

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Human locomotion is adaptive in any external environment or different terrains, which has been widely investigated. For example, people can walk at different walking speeds in each leg on a split-belt treadmill. However, human locomotor behaviors are passively adapted during the split-belt treadmill walking. Therefore, the knowledge of how humans actively adjust the flexibility of locomotion is limited by using the split-belt treadmill. To address this gap, this study investigated the flexibility of locomotion by using a 4-lb ankle weight on the dominant leg to induce the asymmetric walking pattern when walking on the inclined, declined, and level treadmill. Twenty healthy young participants were recruited for this study. Six conditions (walking on the level, 15% grade of the inclined treadmill, 15% of the declined treadmill with/without wearing 4-lb loading on the dominant leg) were randomly assigned to participants. Step length symmetry (SLS) and step time symmetry (STS) were dependent variables. There was a significant interaction between the effect of unilateral limb loading and the effect of inclinations on SLS and STS ($p < 0.0001$). The post hoc comparisons indicated that unilateral limb loading caused an asymmetric walking pattern when walking on the level and the inclined treadmill but not on the declined treadmill. This phenomenon could be explained by increased levels of active control when walking on the declined treadmill to eliminate the effect of unilateral limb loading by reducing the step length and step time. The current result illustrates the possibility of using the declined treadmill to readjust the symmetric walking pattern in people who walk asymmetrically.

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CHAPTER 1: INTRODUCTION

1. Introduction of Human Locomotion

1.1. Normal Gait Pattern

Walking is an important human behavior, and we cannot effectively perform activities of daily living, sports, social activities, and many occupations without walking. In the physical therapy clinic, physical therapists always need to analyze the performance of walking for subjects or patients. Gait is defined as "a particular way of walking" in the Cambridge Dictionary. Healthcare workers always explained gait analysis as walking performance to their patients so patients can easily understand.

In fact, it is not an easy to analyze the normal gait pattern. It has been shown that different gender, age, or other factors would affect gait performance, such as speed, joint motion, ground reaction force, etc. People of all ages should have a similar gait pattern, but the gait parameters are different. For instance, younger adults have faster walking speed, lesser variability on gait parameters (e.g., lesser stride length variability, Virmani et al., 2018), and increased cadence, larger step and stride length, compared with elderly population (Herssens et al., 2018). Younger people are more stable on their gait and fluctuate less over time compared to the elderly (Almarwani, et al., 2016). In addition, gender also has significant effect on gait performance. For example, males usually walk faster with longer stride length than females. There is also a significant effect of gender on gait symmetry, but the effect sizes of gender on gait symmetry were smaller, compared with effect sizes of age. Thus, the age is the main factor on affecting gait symmetry than gender for normal healthy adult population (Kobayashi et al., 2014).

Normal gait patterns should be symmetrical but seldom people do exhibit perfect gait symmetry. Research shows a normal gait pattern is symmetrical both spatially and temporally and the differences of interlimb in vertical forces and temporal parameters measures usual less than 6% (Herzog et al., 1989). The spatial gait variability includes step length, step width, etc. and temporal gait variability includes step time, swing time, stance time, double support time, etc. (Almarwani, et al., 2016). Gait is characterized by periods of loading and unloading of the lower extremities to move around, providing independence. Gait analysis is based on a gait cycle. One gait cycle is measured from heel-strike to heel-strike of one lower extremity, which consists of the stance phase and swing phase.

Stance phase is the period of time that the foot is on the ground, and about 60% of one gait cycle is spent in the stance phase. During the stance phase, the leg accepts body weight and provides single limb support. It includes:

- Initial Contact (aka heel strike, occurs when the foot contacts the ground)
- Loading Response (initial double limb support, occurs after initial contact until the elevation of opposite limb, body weight is transferred on to the supporting limb)
- Mid-stance (single-limb support, from the elevation of the opposite limb until both ankles are aligned in the coronal plane)
- Terminal-stance (single-limb support, begins when the supporting heel rises from the ground and continues until the opposite heel touches the ground)
- Pre-swing (second double limb support, from initial contact of the opposite limb to just before the elevation of ipsilateral limb)

Swing phase is the period of time that the foot is off the ground moving forward, and about 40% of one gait cycle is spent in the swing phase. During the swing phase, the limb advances. It includes:

- Initial Swing or Toe-off (from the elevation of the limb to point of maximal knee flexion)
- Mid-swing or Foot Clearance (following knee flexion to point where the tibia is vertical)
- Terminal Swing (from a point where the tibia is vertical to just before initial contact)

1.2. Gait Analysis

Gait analysis is a quantitative assessment for gait disturbances in the clinic. It provides important information for healthcare providers, such as functional diagnosis, assessment for treatment planning, and monitoring of disease progression (Baker et al., 2016). There are different methods to perform a gait analysis.

1.2.1. Analyzing gait through visual observation. Human eyes are a sensitive way to observe a person’s walking performance. It can detect the gait deviation from a normal gait pattern. It is very common for physical therapists to use observation to perform gait analysis in the clinic due to space and time limitations. For instance, physical therapists are trained to recognize Trendelenburg gait if the patient walks with one side of the pelvis dropped. Physical therapists understand that this patient has weak muscles of the gluteus medius and gluteus minimus muscles, which is a defective hip abductor mechanism causing the abnormal gait pattern (Gandbhir et al., 2020). In this way, physical therapists know how to develop the plan of care focusing on therapeutic exercises and gait training to improve the strength of gluteus muscles and correct the patient’s gait performance. However, gait analysis by human eyes lacks the ability to quantitatively track the change of gait pattern after a period of rehabilitation.

1.2.2. Analyzing gait with computers, digital cameras and other electronic devices. The gait analysis system provides an objective and quantitative method to perform the analysis, which is safe, reliable, and accurate. It is very common to use in the research lab to collect data from various types of patients who have gait deficits as well as healthy participants. Using the gait analysis system to perform the gait assessment is a standardized and quantitative method. Nowadays, there are two types of gait analysis systems commonly used by physical therapists or rehabilitation researchers: pressure sensing walkways or camera-based systems.

- Pressure sensing system: For instance, Zeno™ Walkway Gait Analysis System[1] detects pressure data during gait, during balance, and additional movement protocols. People typically will be required to walk on a 10-meter Walkway several times. The Walkway will record the pressure of the patient's feet to analyze the gait performance. The Quantitative Gait Analysis (QGA) data collected by the Zeno Walkway system adds to the physical therapist's tools with measures including temporal and spatial parameters, relative pressure, step and stride, gait phase, gait cycle, velocity, and Center of Pressure (COP).[2]
- Camera-based gait analysis system: A motion capture system uses three-dimensional optoelectronic tracking system (based on reflective markers placed on the surface of the body in relation to some specific bony landmarks) and incorporates multicomponent force platforms. It provides the quantitative temporal and spatial data, as well as joint kinematics (joint angles) and kinetics (the moments that the muscles and other soft tissues must be exerting at the joints). Data collection using a motion capture system usually takes longer

[1] Zeno walkway gait analysis system » ProtoKinetics. Protokinetics.com. Published April 9, 2018. Accessed December 23, 2020. https://www.protokinetics.com/zeno-walkway/
[2] Zeno walkway & PKMAS for physical therapists » ProtoKinetics. Protokinetics.com. Published January 16, 2019. Accessed December 23, 2020. https://www.protokinetics.com/rehab/

compared with the walkway. It requires the researcher to attach the reflective markers. Then, a calibration trial must be performed with the participants in the center of the capture volume. The motion capture system commonly requires a specialized room with the cameras and computers, which is the reason that the system is used to collect data for research instead of as a method for gait analysis in the physical therapy clinic. The motion capture system also can be set up in a different environment to analyze the gait of subjects, such as treadmill walking, stairs navigation, crossing obstacles, turning, etc. It can also be combined with electromyography (EMG) system to analyze the muscle activities during walking activity.

2. Treadmill Walking

2.1. Definition and History of Treadmill Walking

A treadmill is a device generally used for walking, running, or climbing (uphill or downhill walking) while people stay in the same place. Treadmills were introduced before the development of powered machines to harness the power of animals or humans to do work, often a type of mill operated by a person or animal treading the steps of a treadwheel to grind grain.

The first US patent for a treadmill "training machine" (#1,064,968) was issued on June 17, 1913. In 1952, the forerunner of the exercise treadmill was designed to diagnose heart and lung diseases, which was invented by Robert Bruce and Wayne Quinton at the University of Washington. In 1968, Kenneth H. Cooper published a research about the benefits of aerobic exercise, which provided a medical argument to support the commercial development of the home treadmill and exercise bike.[3] In the 1980s, treadmill training with neurological patients was used and described in clinical settings (Finch et al., 1985). In 1987, Barbeau and Rossignol trained spinalized (T3) cats to walk with their hindlimbs on a treadmill, and the results revealed, even as adults, cats could recuperate locomotor functions of the hindlimbs with BWS of the hindquarters and plantar digitigrade placement of the feet after spinal transection (Barbeau et al., 1987). Since then, treadmill training with partial body weight support (PBWS) has been more and more studied as an intervention to help the recovery of gait impairments in patients after stroke. In addition, treadmill walking with a three-dimensional (3D) motion capture system (and force plate) is popular for researchers to analyze the difference between normal and abnormal gait patterns and provide the evidence for clinical interventions. For instance, treadmill training is a method to treat gait impairments with post-stroke patients, where patients after stroke walk on a treadmill with or without PBWS system.

2.2. Treadmill Walking vs. Overground Walking

Treadmill walking as a walking training method has become more and more popular to treat the gait impairments of patients in the clinic with stroke or spinal cord injury. The final goal of treadmill training is to help patients return to normal walking patterns in daily overground walking activities. In recent studies, the evidence showed there are some differences between treadmill walking and overground walking (Lee and Hidler, 2008; Riley et al., 2007). Lee and Hidler compared the differences between overground and treadmill walking in healthy individuals (Lee and Hidler, 2008). They found that people had a longer stance time and shorter swing time under the overground walking condition. However, other spatiotemporal parameters

[3] En.wikipedia.org. 2021. Treadmill - Wikipedia. [online] Available at: <https://en.wikipedia.org/wiki/Treadmill> [Accessed 28 March 2021].

during overground walking did not have significant differences compared with the treadmill walking condition, such as walking speed, step time, double-limb support time, cadence, and stride length. They also compared the joint kinematics in the sagittal plane and found that only knee range of motion was significantly different between treadmill walking and overground walking. Besides, they also analyzed the joint moments, joint powers, ground reaction forces, and muscle activity. Overall, they suggested that the temporal gait parameters and kinematic patterns are similar between treadmill walking and overground walking, but muscle activation patterns, and joint moments and powers used to achieve these movement patterns are often different. They mentioned that although there are several differences between these two walking conditions, the overall kinematic and muscle activation patterns appear to be similar enough that training people with neurological injuries, such as stroke and spinal cord injury, on a treadmill appears to be justified.

Another research study (Riley et al., 2007) also compared the kinematic and kinetic parameters between the overground and treadmill walking in healthy subjects. They had the same conclusion that treadmill walking is qualitatively and quantitatively similar to overground walking after compared the parameters. Although there are some differences in the kinematic parameters and the kinetic parameters, especially in the kinetic parameters, the magnitudes of these differences are within the range of repeatability of measured kinematic parameters. Thus, the mechanics of gait for treadmill walking and overground walking are very similar.

2.3. Inclinations of Treadmill Walking

Daily walking requires people to walk on different surfaces and slopes, such as uphill and downhill walking. Different inclinations of walking require different body mechanics and demands. For instance, uphill walking needs more energy than level walking, and downhill walking needs people to cope with inertial forces acting upon the body. An advantage for using the treadmill to perform the gait analysis is that the slope of the treadmill can be adjusted to simulate uphill and downhill walking. But is there any difference in gait patterns or gait parameters among different inclinations of treadmill walking? A recent research compared the gait parameters for uphill and downhill walking using a self-paced treadmill for young healthy participants (Kimel-Naor et al., 2017). A self-paced treadmill uses a feedback-controlled treadmill that allows participants to walk on the treadmill at their preferred speed. Another research found that gait pattern was similar for self-paced treadmill walking and fixed speed treadmill walking, but the walking speed varied more during the self-paced treadmill walking (Sloot et al., 2014). Kimel-Naor S, et al. pitched the platform of the treadmill at +10°, −10°, and 0° respectively to simulate the uphill, downhill, and level walking along with a motion capture system combined with 2 force plates and a virtual reality system (synchronous corresponding elevation of a projected scene of a one-lane road on a bright day). Young healthy subjects were required to walk in self-paced mode in three trials. Each trial began with 15–35s of level walking and then followed by 1 minute of walking at one of the three inclinations: 0° inclination (level walking), +10° inclination (uphill walking), and −10° inclination (downhill walking). The researchers collected spatiotemporal gait parameters to perform the gait analysis, including step length, stride length, swing duration, stance duration, hip angle, knee angle, ankle angle, pelvic tilt in the sagittal plane, pelvic tilt in the frontal plane, pelvic girdle rotation, trunk tilt in the sagittal plane, trunk tilt in the frontal plane, shoulder girdle rotation, gait speed, cadence, elbow angle, shoulder angle, gait asymmetry, and gait variability. They found that the uphill treadmill walking had more impact on the gait kinematics than the downhill treadmill walking because all joint angles showed significant differences during the uphill treadmill walking.

During the downhill treadmill walking, only appendicular skeleton related joint angles, with the exception of pelvic angles, showed significant differences. However, gait coordination parameters were not affected by the walking slope, explained by the gait asymmetry, left-right coordination, and stride time (gait variability) are unaffected by the walking slope since they were similar in all three inclination conditions. In conclusion, the inclination did not affect the gait symmetry among different inclinations of treadmill walking.

2.4. Advantages and Disadvantages of Using a Treadmill to Perform Gait Analysis or Gait Training in Healthy Adults as well as in Patients with Walking Impairments

Gait analysis is increasingly recognized as an important assessment tool for developing therapies for healthy adults, sports injuries, patients with numerous movement disorders, and neurodegenerative diseases. As mentioned before, there are different methods using for gait analysis by researchers or healthcare providers, such as visual observation by requiring people walking on the ground or camera-based gait analysis system. Typically, camera-based gait analysis system requires people to walk on a treadmill and then collecting data in various conditions. There are some advantages by using treadmill to perform gait analysis or gait training compared by walking on ground, including:

A. Collecting continuous quantitative data: Treadmill walking combined with a motion capture system and force plates is a common method to use to perform gait analysis in a gait lab. Using those instruments together, researchers are able to collect more kinematic and kinetic data compared with walkway (pressure mat only), such as joint motion, joint angles. More consecutive gait cycles can be recorded in a short period of time, which increases the data collection efficiency. Moreover, collecting multiple gait steps increases data reliability. In addition, using treadmill walking to train gait can improve training efficiency and permit patients who have gait impairments to perform more steps within a training session compared with conventional overground walking training. For instance, a study (Hesse S and Werner C. 2003) reported that in a 20-minute session, patients after stroke could perform up to 1000 steps during the treadmill training, compared with only 50 to 100 steps in the conventional physical therapy using a neurophysiological approach.

B. Performing specific task: The inclination can be adjusted in the treadmill to simulate uphill and downhill walking, so the uphill and downhill gait can be analyzed in healthy adults or patients who have gait impairments. Besides, other parameters such as speed can also be changed during the gait analysis so researchers can compare the gait performance in different walking speeds, or even performing a running analysis. In addition, the amount of body weight support by PBWS system, and amount of assistance provided by therapists can also be adjusted. In order to provide enough training intensity for patients, physical therapists can adjust these parameters during the training based on the patient's situation.

C. Improving walking speed and endurance but NOT improving walking independently with patients with spinal cord injury (SCI): A systematic review (Mehrholz et al., 2017) compared the effectiveness of BWS treadmill training and robotic-assisted gait training with overground gait training and other forms of physical therapy in people with traumatic SCI, and the results revealed compared with patients with SCI not receiving treadmill training, patients with SCI who received treadmill training (with or without body-weight-supported) were not more likely to improve their ability to walk independently. However, walking speed and endurance may improve slightly in the short term. In other words, patients with SCI who can ambulate independently appear to benefit the most from treadmill walking intervention to improve their walking speed and endurance, instead of patients who are dependent in walking at the beginning of treatment. In addition, a recent study (Lura et al., 2019) showed body weight supported treadmill training (BWSTT) and conventional gait training (CT) resulted in significant improvements during therapy with an overall average Functional Independence Measure (FIM) score increased of 3.4 for acute post-stroke patients, but both interventions had similar results relative to the clinical measure outcomes - FIM, and they were not clinically superior to the other forms of gait therapy for improving walking ability in patients with sub-acute stroke. In the clinical practice, the treatment of gait impairments should consider comfort and safety for the patients and as well as patient-specific factors.

D. Improving Functions in the upright position using BWSTT: Askim et al. (2014) had a study about physical activity early after stroke and its association to functional outcome 3 months later, which revealed that every 5-minute increase in time spent in bed was associated with a 4% deterioration on the Modified Rankin Scale score (mRS, ranging from 0 to 6, where 0 is normal function and 6 denotes death) three months later. Therefore, increasing the time spent on an upright position every day could potentially have a great impact on functional recovery over time. Moreover, another study also found that overall increasing the time spent in the upright position was associated with increasing independence (mRS) and improved physical function (Short Physical Performance Battery). BWSTT is a great intervention to maintain the upright position of patients with stroke and improve their function.

In the literature, there are many advantages by using treadmill to perform gait analysis or gait training, but some disadvantages have been observed during gait analysis or gait training in healthy adults as well as in patients with walking impairments, including:

A. Space requirement: The treadmill walking to perform gait analysis require a lab room to set the treadmill with a motion capture system and force plates. Typically, treadmill walking gait analysis combined with a motion capture system and force plates need a room to set up the camera and force plates. For this reason, that it is uncommon to use those instruments to perform gait analysis in a clinic.
B. Specialty training: Before collecting data or gait training, researchers need to be trained on how to collect data and perform data analysis, which is essential to maintain safety for all participants as well as collecting valid data. For instance, the researchers need to put reflection markers at the bony landmarks, such as lateral malleoli, lateral aspect of the heel, axis of knee joint, etc. and they need to perform a calibration after setting all the markers and before the testing.
C. Time-consuming if performing with non-ambulant patients: Treadmill training takes some time to set up the harness system with patients after stroke, particularly in non-ambulant patients with poor standing balance. It decreased the time for skilled training with patients by using treadmill during the training session.
D. More staffs needed if performing with non-ambulant patients: BWSTT requires at least two members of staff when performing gait analysis or gait training with patients who have gait deficits, including 1 physical therapist, to deliver the treadmill intervention. For instance, a physical therapist required to assist the hemiplegic lower extremity when performing gait analysis or gait training with patients who have stroke and another staff

is required to collect data with the computer. It is difficult to deliver the treadmill training interventions with patients when staffing levels are reduced for various reasons, such as busy schedule in the clinic, sickness absence, holiday leave, etc.

3. Adaptation of Human Locomotion

Human locomotion is adaptable to any changes in the environments as well as unfamiliar environments in normal healthy individuals. This adaptability has been widely verified by studies requiring participants to walk at different walking speeds in each leg on the split-belt treadmill (Choi et al., 2009; Morton and Bastian, 2006; Malone and Bastian, 2010; LeBel et al., 2008; Reisman et al., 2005; Reisman et al., 2007; Torres-Oviedo and Bastian, 2010) or by putting an ankle weight on one leg (Mukherjee et al., 2011). The split-belt treadmill has two independent belts, one under each leg, so that people can walk on those belts moving at the same speed or at different speeds (Helm et al,. 2015).

Morton and Bastian (2006) indicated that upon the introduction of split-belt walking paradigm perturbed walking environment, participants replaced their existing motor command to create a new motor command for adapting to this specific environment by trial-and-error practices (Morton and Bastian, 2006). This process is called adaptation (Choi et al., 2009; Morton and Bastian, 2006; Malone and Bastian, 2010; LeBel et al., 2008; Reisman et al., 2005; Reisman et al., 2007; Torres-Oviedo and Bastian, 2010). However, when the perturbed walking environment was removed, a new series of trial-and-error practices for humans is required to return the walking pattern to its original state. This process is defined as de-adaptation (Choi et al., 2009; Morton and Bastian, 2006; Malone and Bastian, 2010; LeBel et al., 2008; Reisman et al., 2005; Reisman et al., 2007; Torres-Oviedo and Bastian, 2010). Adaptation and de-adaptation represent one aspect of the flexibility of human locomotion. This flexibility of human locomotion is speculatively controlled by the cerebellum (Morton and Bastian, 2006), motor cortex (Reisman et al., 2007), sensory areas of the brain (Torres-Oviedo and Bastian, 2010; Mukherjee et al., 2011), conscious cerebral resources (Malone and Bastian, 2010), and spinal cord (Morton and Bastian, 2006).

It has been shown that the spinal cord and the cerebellum serve different roles for the flexibility of locomotion (Morton and Bastian, 2006). The spinal cord has been suggested to play a role in feedback-driven locomotor adaptation (Lam et al., 2006). For instance, when spinalized cats walk on the split-belt treadmill, these cats could quickly adjust the stance time on each side of their legs to adapt to a speed difference between the left and right belts (Frigon et al., 2013). In addition, human infants, who have been suggested to primarily use feedback-driven control, also can walk on the split-belt treadmill smoothly (Vasudevan et al., 2011). Moreover, patients with cerebellar damage demonstrate the ability to walk at different speeds on each leg on the split-treadmill (Morton and Bastian, 2006).

To summarize the abovementioned studies, the intact spinal cord is the reason why human infants, patients with cerebellar damage, and spinalized cats can still walk at a different speed of each side of the body based on the real-time feedback from the sensory systems, primarily somatosensory system that is in direct foot contact with the treadmill belt (Mukherjee et al., 2016). However, for patients with cerebellar damage, they cannot adjust some specific gait parameters to adapt to the split-belt treadmill walking, such as the step length, which is an indicator for damaged feedforward-driven locomotor adaptation because the study from Morton and Bastian (2006) showed healthy people demonstrated some reactive adjustments of gait parameters (such as stride length, time in stance) to adapt the novel difference in treadmill belt speeds, but revealed feedforward adaptation of other parameters (such as step length, time in double support, and interlimb phase relationships). Therefore, the cerebellum may play an important role to control the feedforward-driven locomotor adaptation, which controls step-by-step locomotor adaptation and step length variability (Morton and Bastian, 2006).

In order to achieve successful locomotor adaptation, a capability to resolve the sensory mismatch conflict between the visual and proprioceptive systems is required. A study showed that removing the vision during split-belt walking enhanced the learning effect from the treadmill walking to the overground walking (Torres-Oviedo and Bastian, 2010). Another study even showed that adding the optic flow when walking on the treadmill with an ankle weight (10-lb) on one leg reduced the asymmetric walking pattern (Mukherjee et al., 2011). A possible explanation is that adding or removing the vision in a perturbed walking environment changes a person's perception to recalibrate their reference through exploring surroundings randomly until an unexpected reward is encountered (Torres-Oviedo and Bastian, 2010).

Consciousness also affects the flexibility of human locomotion. With or without the conscious effort involved, the outcomes of adaptation are also different (Malone and Bastian, 2010). Interestingly, distraction from the task which forces more conscious efforts slows spatial adaptation only (step length or step symmetry), but not temporal adaptation (phasing or shift timing) (Malone and Bastian, 2010). This result suggests that the adaptation of spatial control is more sensitive to the levels of conscious effort in comparison with temporal control (Malone and Bastian, 2010).

Walking on an inclined or declined surface is a common daily activity. To walk on different inclinations requires different physical demands – walking on an inclined surface consumes more energy than walking on the level surface (Minetti et al., 2002), and running on the declined surface requires specific control to handle the inertial forces acting upon the body (Gottschall and Kram, 2005). Specifically, walking on the declined surface absorbs greater shear-force during the power absorption phase based on controlling the anterior rotation of the tibia to hold back the downward motion of the body than walking on the level or inclined surfaces (McIntosh et al., 2006). Also, one study indicated that the oxygenation level is greater in the areas of the prefrontal and sensorimotor cortex when walking on a declined surface compared with walking on the level or the inclined walking (Mazerie et al., 2012). It suggests that walking on a decline may require activations in the prefrontal and sensorimotor areas to cope with attention-demanding locomotor tasks (Mazerie et al., 2012).

4. Unilateral Ankle Weighting or Unilateral Limb Loading Causing Asymmetrical Walking Pattern

Unilateral ankle weighting or unilateral limb loading could change the gait pattern in spatiotemporal parameters. Unilateral limb loading with an ankle weight has been found to change the spatial parameters. A study compared spatiotemporal gait parameters by requiring subjects walking in the level treadmill with unilateral ankle weight. The evidence showed loaded limb demonstrating significantly shorter strides and the unloaded limb exhibiting significantly longer strides (Nessler et al., 2015). Another study had the same results, compared with the unloaded side, the loaded side had a shorter stride length (Claremont et al., 1988). In addition, to adapt the unilateral limb loading, subjects increased their number of steps (cadence) (Mukherjee et al., 2011). Unilateral limb loading with an ankle weight can also change the temporal parameters. Smith et al. (2007) determined the amount of time needed for people to become well accommodated to asymmetrical changes in lower extremity inertial properties. In their study, participants required to walk on the level treadmill with a weight on right ankle. The results indicated that the loaded limb increased the swing time and reduced the stance time; the unloaded limb reduced the swing time and increased the stance time. In other words, the loaded limb takes a longer time on the swing phase and a shorter time on the stance phase compared with the unloaded side (Smith et al., 2007). During the level treadmill walking with unilateral limb loading, individuals changed gait parameters with longer swing time, shorter stance time, and shorter stride length on the loaded side, as well as increased cadence, which are also noted to be very typical pattern for persons following stroke.

After the literature review, there is a paucity of evidence about gait performance in inclined or declined treadmill combined with unilateral limb loading.

5. The Knowledge "Gap" of Recent Literature

Since 1980s, the research of treadmill training has been provided solid evidence to recommend the use of treadmill for clinical training. However, only one study (Sombric et al., 2019) indicated that the flexibility of human locomotion indeed exists when walking on the inclined and declined surfaces by adjusting the step length symmetry on a split-belt treadmill. Importantly, walking on the inclined surface with two different walking speeds for each leg enhances the adaptation in comparison with walking on a declined and level surface due to the increased propelling force during the push-off phase of the gait cycle (Sombric et al., 2019). However, when human walk at different walking speeds for each leg on the split-belt treadmill, their locomotor behaviors are passively changed by the motor-driven treadmill (feedback-driven). Therefore, it is difficult to understand how people adjust the flexibility of locomotion actively under certain physical and conscious demands by using the split-belt treadmill. Studies already suggested that manipulating the sensory stimuli and perturbing the locomotor environment could shift the locomotor control from passive to active status (Philbeck et al., 2001; O'Connor and Kuo, 2009). However, there is no current research to study how people with unilateral limb loading can adjust their flexibility of locomotion actively under physical and conscious demands by using a regular treadmill.

6. Purpose and Hypothesis

In order to address the knowledge gap, instead of using the split-belt treadmill, this study investigated the flexibility of locomotion by using a 4-lb ankle weight (Skinner & Barrack, 1990) on the dominant leg to induce the asymmetric walking pattern when walking on the different inclinations of a regular treadmill (inclined, declined, and level). The aim of this study was to determine how participants adapt gait performance by changing gait parameters when walking with unilateral limb loading as well as changed inclination.

It is hypothesized that unilateral limb loading leads to the asymmetric walking pattern with asymmetrical step length and step time for bilateral lower extremities on all the level, inclined, and declined treadmill walking conditions.

CHAPTER 2: METHODS

1. Participants

Twenty healthy young participants (age: 24.7 ± 2.2 years; height: 1.73 ± 0.08 m; mass: 68.92 ± 12.07 kg, 12 females and 8 males) were recruited for this study. Participants were free from any neurological or musculoskeletal problems and no recent history of lower extremity injuries that might have affected their walking, such as having osteoarthritis, gout, neuropathy, vertigo, dementia, stroke, Parkinson disease, vestibular disorders, and any other diseases or circulation issues. In addition, a Montreal Cognitive Assessment (MoCA) was given to all participants. The MoCA is a 30-point questionnaire that is used in the clinical and research setting to measure cognitive impairment (Nasreddine et al., 2005). For those participants whose scores were above 26 out of 30 on the MoCA, they were included in this study. This study was approved by the University of Nebraska Medical Center Institutional Review Board and followed the related regulation of the board (IRB# 006-18-FB).

2. Experimental Materials

An infra-red eight-camera Qualisys motion capture system (Qualisys AB, Gothenburg, Sweden) and spherical retro-reflective markers were used to collect 3D kinematic data at 100Hz using Qualisys Tracker Manager (QTM) software (Qualisys AB). Two retro-reflective markers were placed on heels, and the second metatarsophalangeal joint (toe) of both legs to measure the spatial-temporal gait parameters: step length (SL) and step time (ST). The heel strike was defined at the instant as the horizontal heel displacement reached a maximum (Parks et al., 2019). The toe-off was defined as the lowest vertical position of the trajectory (Parks et al., 2019). The step time was the period from the heel-strike to the toe-off of the ipsilateral leg. In this study, the spatial-temporal parameters for a total of 100 gait cycles were used. Also, step length variability and step time variability were calculated as the coefficient of variation (standard deviation of step parameter for 100 gait cycles * 100) / (mean value of the step parameter for 100 gait cycles). All kinematic parameters were determined using the custom MATLAB R2011a (MathWorks, Natick, MA) (Parks et al., 2019). A safety lanyard was attached to the subject's pants; the treadmill would immediately ramp down to a full stop when the safety lanyard is disconnected. The participant could hold the handrail if they felt imbalance. All subjects were instructed to wear a gait belt. If participants felt any discomfort during walking overground or on the treadmill, participants could stop the data collection at any time.

To quantify interlimb coordination, the indices of step length symmetry (SLS) and step time symmetry (STS) were quantified (Eqs. 1, 2 respectively). The positive SLS value indicated that the step length was shorter in the dominant leg than in the non-dominant leg. The positive STS value indicated that the step time was shorter in the dominant leg than in the non-dominant leg. The dominant leg was defined by asking, “which leg did you prefer to kick a soccer ball?”.

$$\mathrm{SLS} = \frac{SL\_non\_dominant\_leg - SL\_dominant\_leg}{SL\_non\_dominant\_leg + SL\_dominant\_leg} \quad (1)$$

$$\mathrm{STS} = \frac{ST\_non\_dominant\_leg - ST\_dominant\_leg}{ST\_non\_dominant\_leg + ST\_dominant\_leg} \quad (2)$$

3. Experimental Protocol

Prior to the data collection, each participant walked on the treadmill (Biodex RTM 600, Shirley NY, USA) for 5 minutes to determine their preferred walking speed (PWS, mean ± SD: 0.94 ± 0.13 m/s, range: 0.67-1.16 m/s). Participant stood on the sides of the treadmill without touching the belts and then stepped on the moving (0.8 m/s) treadmill while holding the handrail. After the subjects started walking on the treadmill without holding the handrail, experimenters asked the participant to evaluate the speed as follows: “Is this walking speed comfortable like walking around the grocery store?” The treadmill velocity was increased or decreased based on subjects’ responses (+0.1 or -0.1 m/s for each increment). Once the PWS was attained, subjects walked on the treadmill continuously for 5 minutes of familiarization. After familiarization, six conditions (walking on the level treadmill; walking on the 15% grade of inclined treadmill; walking on the 15% of declined treadmill; walking on the level treadmill with wearing 4-lb ankle weight on the dominant leg; walking on the 15% grade of inclined treadmill with wearing 4-lb ankle weight on the dominant leg; and walking on the 15% grade of declined treadmill with wearing 4-lb ankle weight on the dominant leg; Figure 1) were randomly given to participants. Each condition lasted for 2 minutes. Between conditions, participants were asked to take a two-minute mandatory rest to wash out the potential learning effect from the inclined walking, the declined walking or the walking with wearing a unilateral ankle weight. The limitation of 4-lb of ankle weight on the dominant leg was restricted for safety reasons by the University of Nebraska Medical Center Institutional Review Board. In the current study, all twenty participants identified their right legs as their dominant legs.

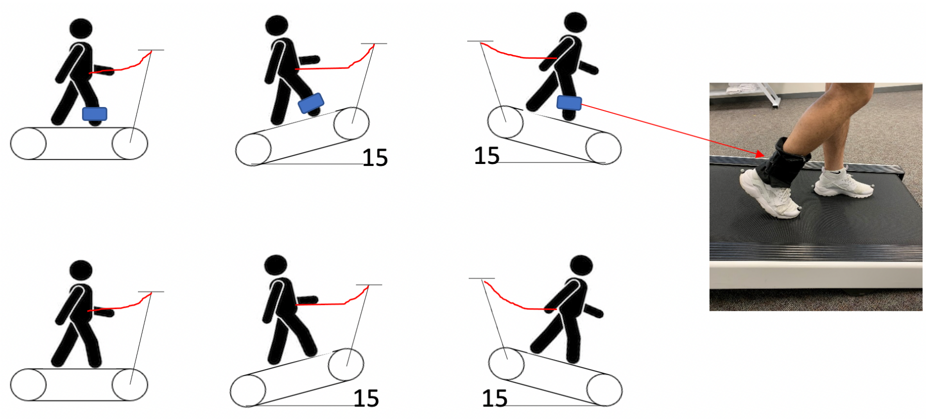

Figure 1: The six condition of experimental diagram. The blue box represents the 4-lb ankle weight. The angle of inclination and declination is 15% grade.

4. Statistical Analysis

Normality tests were run to ensure data did not violate any assumption of using ANOVA. Then, a three-way repeated measure ANOVA (with or without wearing a 4-lb ankle weight x 3 different conditions – level, inclined, declined treadmill walking x 2 leg sides - the dominant and non-dominant leg) was used to investigate the interactions among the effect of dominant leg, unilateral limb loading, and different locomotor conditions on the mean values of step length, step time, step length variability, and step time variability. Also, a two-way repeated measures ANOVA (with or without wearing a 4-lb ankle weight x 3 different conditions – level, inclined, declined treadmill walking) was used to investigate the interaction between the effect of unilateral limb loading, and the effect of different locomotor conditions on SLS, STS. The significant level was set at 0.05. When a significant interaction was reached, post-hoc pairwise comparisons with Tukey correction were used. To understand the effect size, we used the partial eta squared method, and based on Cohen's guideline, 0.138 represents a large effect size, 0.059 represents a moderate effect size, and 0.01 represents a small effect size (Cohen, 1988; Richardson, 2011).

CHAPTER 3: RESULTS

1. Normality test results (Table 1 and Table 2)

A normality test was performed to confirm that sample data were normally distributed. There were no significant difference (P>0.05) among each group in SLS and STS for six different walking conditions (L_NoW, walking on the level treadmill; I_NoW, walking on the 15% grade of inclined treadmill; D_NoW, walking on the 15% of declined treadmill; L_W, walking on the level treadmill with wearing 4-lb ankle weight on the dominant leg; I_W, walking on the 15% grade of inclined treadmill with wearing 4-lb ankle weight on the dominant leg; and D_W, walking on the 15% grade of declined treadmill with wearing 4-lb ankle weight on the dominant leg).

Table 1: Normality test of SLS for six different walking conditions.

Tests of Normality

	groups	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
SLS	D_NoW	.212	20	.019	.940	20	.239
	L_NoW	.117	20	.200*	.976	20	.871
	I_NoW	.128	20	.200*	.965	20	.650
	D_W	.167	20	.145	.949	20	.354
	L_W	.106	20	.200*	.984	20	.978
	I_W	.177	20	.101	.931	20	.162

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Table 2: Normality test of STS for six different walking conditions.

Tests of Normality

	groups	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
STS	D_NoW	.087	20	.200*	.973	20	.812
	L_NoW	.150	20	.200*	.943	20	.274
	I_NoW	.101	20	.200*	.969	20	.723
	D_W	.115	20	.200*	.959	20	.518
	L_W	.135	20	.200*	.963	20	.600
	I_W	.140	20	.200*	.967	20	.682

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

2. The effect of unilateral limb ankle loading and the effect of conditions on SL and ST (Table 3)

Significant interactions were found among the effect of unilateral limb ankle loading, different legs, and conditions on SL ($F_{2, 38} = 62.83$, $p < 0.0001$) and ST ($F_{2, 38} = 79.67$, $p < 0.0001$). The post hoc comparisons are listed in Table 3.

For the effects of unilateral limb loading on SL and ST, there were no differences in SL and ST on dominant leg and non-dominant leg between unilateral limb loading and no loading condition during walking on the declined treadmill. Compared with no loading condition, both dominant leg and non-dominant leg with unilateral limb loading on dominant leg conditions exhibited decreased SL walking pattern during walking on the level ($p < 0.001$, $p < 0.001$ respectively) and inclined ($p = 0.004$, $p < 0.001$ respectively) treadmill. Similar phenomenon with decreased ST was found for both dominant leg and non-dominant leg with unilateral limb loading on dominant leg conditions during walking on the level and inclined treadmill, when compared with no loading condition.

For the effects of treadmill walking conditions on SL and ST, the results demonstrated inclined and declined treadmill walking decreased SL and ST in comparison with the level walking for both dominant and non-dominant legs.

Table 3: The effect of conditions and the effect of unilateral limb loading on step length and step time.
NS: no significant

Step Length Conditions	Legs	Unilateral Limb Loading	Mean -- Meter (SD)	**The Effect of Unilateral Limb Loading** vs. No Loading	**The Effect of Conditions** vs. Level Walking
Declined	Dominant	No	.457 (.07)	NS	$p < 0.001$
		Yes -- on Dominant leg	.453 (.07)		$p < 0.001$
	Non-Dominant	No	.453 (.07)	NS	$p < 0.001$
		Yes -- on Dominant leg	.461 (.07)		$p < 0.001$
Level	Dominant	No	.547 (.07)	$p < 0.001$	
		Yes -- on Dominant leg	.530 (.07)		
	Non-Dominant	No	.545 (.07)	$p < 0.001$	
		Yes -- on Dominant leg	.582 (.08)		
Inclined	Dominant	No	.566 (.08)	$p = 0.004$	$p < 0.001$
		Yes -- on Dominant leg	.552 (.07)		$p < 0.001$
	Non-Dominant	No	.564 (.07)	$p < 0.001$	$p < 0.001$
		Yes -- on Dominant leg	.593 (.07)		NS

Step Time Conditions	Legs	Unilateral Limb Loading	Mean -- Seconds (SD)	**The Effect of Unilateral Limb Loading** vs. No Loading	**The Effect of Conditions** vs. Level Walking
Declined	Dominant	No	.536 (.05)	NS	$p < 0.001$
		Yes -- on Dominant leg	.539 (.06)		$p < 0.001$
	Non-Dominant	No	.539 (.05)	NS	$p < 0.001$
		Yes -- on Dominant leg	.540 (.05)		$p < 0.001$
Level	Dominant	No	.596 (.05)	$p = 0.002$	
		Yes -- on Dominant leg	.581 (.05)		
	Non-Dominant	No	.593 (.05)	$p < 0.001$	
		Yes -- on Dominant leg	.628 (.06)		
Inclined	Dominant	No	.613 (.06)	$p = 0.04$	$p = 0.015$
		Yes -- on Dominant leg	.600 (.06)		$p = 0.002$
	Non-Dominant	No	.610 (.06)	$p < 0.001$	$p = 0.02$
		Yes -- on Dominant leg	.642 (.06)		NS

3. The effect of unilateral limb ankle loading and the effect of conditions on SLS and STS (Figure 2)

Significant interactions were found between the effect of unilateral limb loading and the effect of conditions on SLS ($F_{2, 76} = 71.70$, $p < 0.0001$) and on STS ($F_{2, 76} = 75.75$, $p < 0.0001$). The post hoc comparisons revealed that wearing a 4-lb ankle weight significantly increased the SLS and STS values when walking on a level treadmill ($p < 0.0001$) and when walking on an inclined treadmill ($p < 0.0001$). In addition, among conditions which were wearing a 4-lb ankle weight, significantly higher SLS and STS values were found when walking on the level treadmill ($p < 0.0001$) and walking on the inclined treadmill ($p < 0.0001$) in comparison with when walking on the declined treadmill (Figure 2).

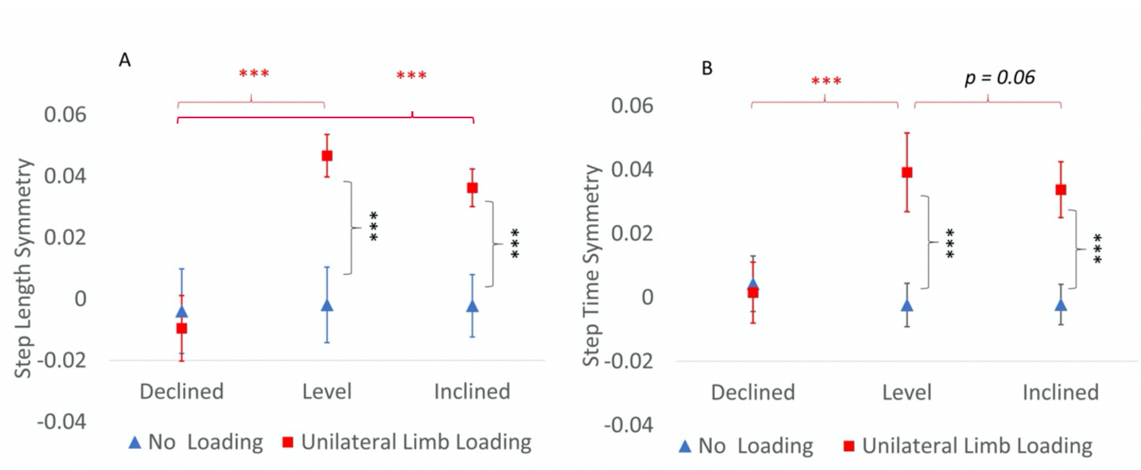

Figure 2: The effect of different conditions (declined, level, inclined -- red asterisk) and the effect of unilateral limb loading (with/without loading – black asterisk) on step length symmetry and step time symmetry. **** represents p < 0.001*

4. The effect of unilateral limb ankle loading and the effect of conditions on step length variability and step time variability (Table 4 and Figure 3)

Significant interaction was found among the effect of conditions and the effect of unilateral limb loading on the marginal means of SL variability ($F_{2, 38} = 4.709$, $p = 0.015$) only. A condition effect was found on the marginal means of ST variability ($p < 0.0001$). The post hoc comparisons are listed in Table 4.

For the effects of conditions on SL variability and ST variability, the results showed increased SL variability and increased ST variability in declined ($p < 0.001$, $p < 0.001$ respectively) and inclined ($p < 0.001$, $p < 0.001$ respectively) treadmill walking with unilateral limb loading, compared with level treadmill walking with unilateral limb loading. Similar phenomenon of increased SL variability and increased ST variability were found in both declined and inclined treadmill walking with no loading condition.

For the effects of unilateral limb loading on the spatiotemporal variability measures, the results only showed the SL variability were significantly lower when walking on the declined treadmill with the unilateral limb ankle loading ($p = 0.004$) than walking on the declined treadmill with no loading condition. However, there was no significant difference on the level or inclined treadmill walking condition. There was no significant difference on the declined, level, or inclined treadmill walking condition on ST variability.

Table 4: The effect of conditions and the effect of unilateral limb loading on marginal means of step length variability and step time variability. NS: no significant

Step Length Variability

Loading	Conditions	Mean (SD)	**The effect of conditions** Vs. Level walking	**The effect of Loading** vs. No Loading
Yes	Declined	6.690 (1.25)	$p < 0.001$	$p = 0.004$
	Level	2.308 (0.79)		NS
	Inclined	3.173 (1.32)	$p < 0.001$	NS
No	Declined	7.596 (1.39)	$p < 0.001$	
	Level	2.259 (0.67)		
	Inclined	3.083 (0.92)	$p < 0.001$	

Step Time Variability

Loading	Conditions	Mean (SD)	**The effect of conditions** Vs. Level walking	**The effect of Loading** vs. No Loading
Yes	Declined	3.411 (0.89)	$p < 0.001$	NS
	Level	2.426 (0.81)		NS
	Inclined	3.239 (1.28)	$p < 0.001$	NS
No	Declined	3.729 (1.04)	$p < 0.001$	
	Level	2.421 (0.71)		
	Inclined	3.323 (1.07)	$p < 0.001$	

No significant interaction was found among the effect of unilateral limb ankle loading, different legs, and conditions on step length variability and step time variability. However, a significant interaction between the effect of unilateral limb loading and the effect of conditions on step length variability was found ($F_{2, 38} = 4.709$, $p = 0.015$; Figure 3) but not on step time variability during the declined treadmill walking condition.

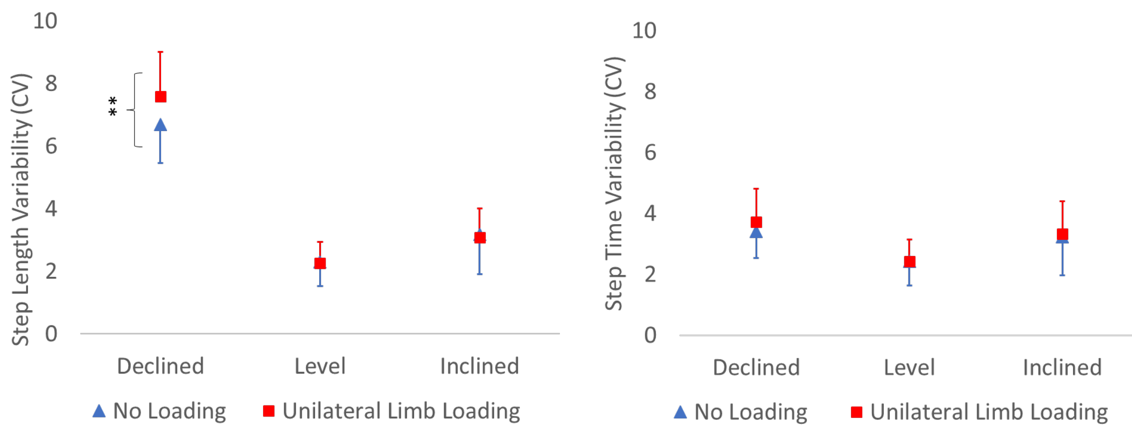

Figure 3: The effect of different conditions (declined, level, inclined -- red asterisk) and the effect of unilateral limb loading (with/without loading – black asterisk) on marginal means of step length variability and step time variability. ** represents p < 0.01

CHAPTER 4: DISCUSSION, LIMITATIONS, and CONCLUSION

1. Discussion

This study aimed to understand the flexibility of human locomotion when walking on inclined, declined, and level surface. The results were in line with previous research, which determined that locomotor adaptations were observed when walking on level and inclined surfaces. Unexpectedly, no locomotor adaptation was found when walking on the declined surface. The results are partially support by the hypothesis that unilateral limb loading leads to the asymmetric walking pattern with asymmetrical step length and step time for bilateral lower extremities on all the level, inclined, and declined treadmill walking conditions.

1.1. Locomotor adaptation when walking on the level and the inclined surfaces

Similar to many studies (Choi et al., 2009; Morton and Bastian, 2006; Malone and Bastian, 2010; LeBel et al., 2008; Reisman et al., 2005; Reisman et al., 2007; Torres-Oviedo and Bastian, 2010; Mukherjee et al., 2011; Mukherjee et al., 2016), participants in this study can adapt a novel locomotor pattern, which was induced by wearing the 4-lb ankle weight on the dominant leg. This new locomotor behavior was similar to someone who rode a skateboard – using one leg to kick the ground to accelerate the body forward and using another leg, which maintains balance on the skateboard. In this study, the non-dominant leg used longer step length and longer step time to move the body forward in comparison with the dominant leg. At the same time, the dominant leg, which wore the 4-lb ankle weight, played a role to stabilize the body (Jung and Lee, 2010). This was why the values of step length symmetry and step time symmetry were all positive when walking on the level and the inclined surface. Although there was no direct evidence from brain activities in the current study, it could be speculated that the cerebellum (related to spatial gait parameters, Morton and Bastian, 2006) and the spinal cord (related to the temporal gait parameters, Frigon et al., 2013) may be involved to make this adaptation.

Interestingly, the values of step length symmetry ($p < 0.001$) and step time symmetry ($p = 0.06$) were much higher when walking on the level surface than when walking on the inclined surface. This result was in contrast with Sombric et al.'s study (Sombric et al., 2019). In their study, walking on the inclined surface induced significantly larger step length asymmetry than walking on the level surface (Sombric et al., 2019). The result might be that the level of active control was different (the cerebellum plays an essential role in predictive locomotor adjustments). When walking on the split-belt treadmill, participants had no choice but to adjust their speed in each leg to catch up the motor-driven treadmill. In this case, the level of active control might be low due to the feedback-driven control mechanism (Morton and Bastian, 2006). However, in the current study, although participants wore a 4-lb ankle weight on their dominant leg, they still had a flexible degree of freedom to actively adjust their step length symmetry when walking at "one" speed for both legs on the treadmill with their preferred walking speed. This was why we observed that the decrement values of step length symmetry and step time symmetry were related to the increment of step length and step time on the dominant leg, which wore the ankle weight when walking on the inclined surface. Thus, in comparison with walking on the split-belt treadmill, walking with unilateral limb loading might exert higher active control (Philbeck et al., 2001; O'Connor and Kuo, 2009).

This study was the first to show this particular control mechanism with healthy young adults, and we speculated that prolonging the step time and increasing the step length on the dominant leg when healthy young adults walk on the inclined surface was to maintain balance (Jung and Lee, 2010). These increments of step length and step time were to increase the area of the base of support and increase the double support time, which were the essential components to maintain balance but needed extra energy to achieve this goal (Minetti et al., 2002).

1.2. No locomotor adaptation when walking on the declined surface

Surprisingly, no locomotor adaptation was observed when walking on the declined surface with unilateral limb loading on the dominant leg – the step length symmetry and step time symmetry showed no differences with or without wearing unilateral limb loading. First of all, our results showed an agreement with previous studies that the step length (Kawamura et al., 1991) and step time (Franz and Kram, 2013) significantly decreased in both the dominant leg and the non-dominant leg when walking on the declined surface in comparison with walking on a level surface. Also, these decrements of step length and step time might be the reason for eliminating the locomotor adaptation. Two rationales could explain this phenomenon: 1) the active control hypothesis (Philbeck et al., 2001; O'Connor and Kuo, 2009), and 2) the level of consciousness (Mazerie J, 2012; Stephan et al., 2002).

In previous studies, it has been suggested that manipulating the sensory stimuli and perturbing the locomotor environment could shift the locomotor control from passive to active control (Philbeck et al., 2001; O'Connor and Kuo, 2009). The active control would be performed by higher cortical centers such as the brain stem and cerebellum to change gait parameters, based on integrated inputs from visual, vestibular, proprioceptive, and other sensors (Bauby and Kuo, 2000). A study indicated that walking on the declined surface changes the perception – steep downhill slopes look shallower from the edge than no slope; in other words, the hills may look much steeper than they are (Li and Durgin, 2009). In addition, in an O'Connor and Kuo study, they suggested that implementing the visual perturbation in the medial-lateral direction induced the active control on locomotion not only in the medial-lateral but also in the anterior-posterior direction (O'Connor and Kuo, 2009). The indicator of active control was the increment of step length variability (O'Connor and Kuo, 2009). In this study, the increment of step length variability might be the direct evidence to demonstrate the presence of active control when walking on the declined surface while wearing a unilateral limb weight. Interestingly, the change of the step time variability was not observed. This result could be explained by how step time was easy to be adjusted by the perception from the treadmill belt speed (feedback-driven, Morton and Bastian, 2006). However, adjusting the step length (feedforward-driven, Morton and Bastian, 2006) might require a high level of the brain control to actively learn to eliminate the perception of the ankle weight; therefore, this might be the reason that high step length variability was observed. Also, based on our observations, it was not difficult for healthy young participants to actively eliminate the perception because 4-lb was not that heavy. Therefore, we speculated that the combination of wearing the weight and the downhill perception might shift the locomotor control from passive to active.

It also has been suggested that walking on a declined surface activates large areas of the prefrontal and sensorimotor cortex (Mazerie et al., 2012). Specifically, the activations in these areas of the prefrontal and sensorimotor cortex highly depend on the levels of consciousness (Stephan et al., 2002). In other words, larger activations in areas of the prefrontal and sensorimotor cortex require a higher level of consciousness (Stephan et al., 2002). In addition, motor behaviors would be completely different if the level of consciousness increases (Stephan et al., 2002). In the current study, walking on the declined surface, which could increase the levels of consciousness, required participants to further exacerbate the changes in the aforementioned spatiotemporal gait characteristics to maintain balance and eliminate the perception of unilateral limb loading (4-lb). A similar finding was reported (Mukherjee et al., 2011) that implementing an optic flow during the treadmill walking with the unilateral limb loading reduced the effect of unilateral limb loading by reducing the cadence and muscle activity because the optic flow triggered the awareness of the perception of self-motion.

Therefore, the phenomenon without locomotor adaptation during declined treadmill walking could be due to a changed of level of consciousness.

2. Limitations and Future Direction of This Study

There are several limitations in this study. The first limitation of this study was the ankle weight of unilateral limb loading. Due to the regulation of the University of Nebraska Medical Center Institutional Review Board, the 4-lb loading was the maximum weight that could be used in the current study. Moreover, based on a previous study (Skinner & Barrack, 1990), 4-lb might be the minimum weight to trigger the asymmetric gait. However, in the current study, the asymmetric gait only was observed when walking on level and inclined surfaces. We did not know how heavy the unilateral limb loading might be for the maximum threshold for triggering the locomotor adaptation when walking on the declined surface.

The second limitation of this study was participants. Only healthy young participants (age: 24.7 ± 2.2 years) were included in this study. As mentioned before, gait parameters are significantly different across different age groups. It will be important to investigate the middle-age or older populations demonstrate similar strategies to younger populations in the future.

The third limitation was that only SLS and STS were used in this study as outcome measures. However, there are many gait parameters that could be used for gait analysis, such as single limb support time, double limb support time, walking speed, cadence, joint motion, joint power, muscles activation, ground reaction force, etc. Additional gait parameters could be considered to demonstrate the same change compared with SLS and STS when walking on different inclination treadmill.

The fourth limitation was that a short duration of treadmill walking (2 minutes) was used for each condition. However, some studies used 4 minutes (Nessler et al., 2015) or even 10 minutes (Meyer C, et al., 2019) to collect the gait parameters during the treadmill walking. It will be important to investigate if the gait parameters would be adapted or changed after a long period walking compared with 2 minutes. In addition, only one trail was used for each condition, we do not know if we can get the same conclusion if we collect the gait parameters with multiple trails for each condition.

The last limitation of this study was inclinations of the treadmill. The inclinations were set up at 15% grade during inclined or declined treadmill walking. However, Kimel-Naor S, et al. (2017) studied the platform of the treadmill at +10° and −10° to simulate the uphill and downhill walking to perform gait analysis (Kimel-Naor et al., 2017). It would be clinically relevant for future studies to exam the difference for gait parameters during different inclinations of treadmill walking (15° vs 10°). Many future studies are warranted to answer these critical research questions about the flexibility of locomotion.

3. Conclusion

In summary, unilateral limb loading leads to the asymmetric walking pattern when walking on level and inclined treadmill, but not on a declined treadmill in the current study; the level of consciousness and active control might be the reasons for this phenomenon. To our best knowledge, this is the first study to demonstrate that walking on the declined surface combined with unilateral ankle weight eliminated the asymmetric walking pattern in healthy young adults. The current result illustrates the possibility of using the declined treadmill to readjust the symmetric walking pattern in people who walk asymmetrically.

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APPENDIX

IRB PROTOCOL # 006-18-FB **Page 1 of 7**

ADULT CONSENT - NON-CLINICAL BIOMEDICAL
Protocol #2

Title of this Research Study
The effect of visual or somatosensory perturbations on balance control differently during standing and walking among healthy young adults, healthy older adults, and fallers: a comprehensive study. (Second title: The effect of the continuous visual perturbation on muscle activation during walking on the flat and tilting surface)

Invitation
You are invited to take part in this research study. You have a copy of the following, which is meant to help you decide whether or not to take part:

- Informed consent form
- "What Do I need to Know Before Being in a Research Study?"
- The Rights of Research Subjects

Why are you being asked to be in this research study?
You are being asked to be in this research study because you are 1) between the ages of 20-40 or 60-75 years; 2) able to understand English; 3) able to follow simple instructions. If you are a healthy adult, you have not been diagnosed with any neurologic or orthopedic problems that influence walking. If you are pregnant, you may not be in this study.

What is the reason for doing this research study?
To understand how your balance changes when walking on inclination or declination of the treadmill with/without wearing a weight (4 pounds) on your dominant leg. The results may help to understand the adaptive capability of human locomotion.

What will be done during this research study?
Prior to doing the walking tests, you will complete an evaluation, the Montreal Cognitive Assessment (MoCA). If your MoCA score is below 26, you will be withdrawn from this study.

You will be asked to complete a questionnaire evaluating how concerned you are about the possibility of falling while performing 10 different activities, scoring your responses on a scale from 1 to 4. The 10 activities are as follows: cleaning the house, getting dressed, preparing simple meals, taking a bath, doing simple shopping, getting in and out of a chair, walking around the neighborhood, reaching into cabinets or closet, answering the telephone, and getting in and out of bed. You also will need to complete a self-health evaluation.

You will walk at your comfortable speeds on the treadmill in all treadmill walking trials. Prior to the data collection, you will walk on the treadmill to determine your preferred walking speed by asking: Is this walking speed comfortable, like walking around the grocery store? The treadmill velocity will be altered based on your answers until reaching the comfortable speed.

You will wear a safety harness attached to the treadmill when you walk on the treadmill.

Total six 2-minute treadmill walking conditions, with/without wearing a weight on the ankle on your dominant leg (4 pounds) x 3 different walking conditions: level walking, ascending walking on a 15% grade of inclination, and descending walking on a 15% grade of inclination. The walking test order will be given to you randomly. The investigators will place 10 retro-reflective markers on your legs. In addition, your motion will be recorded by high-speed motion capture system through these 10 markers. Each condition lasts 2 minutes. The total will be 12 minutes walking on the treadmill. You will be asked to take a 1-minute mandatory rest between trials; however, you can take as long as you need if you feel tired.

What are the possible risks of being in this research study?

You might experience an increase in heart rate, shortness of breath, and possible loss of confidentially might be found in the current study. Other risks of this study include losing your balance, tripping and falling over the treadmill. To ensure your risks are minimized, one minute breaks will be provided to you between trials to alleviate your heart rate and any shortness of breath. The performance will be monitored by research investigators during the research session. In addition, if you cannot walk on the treadmill, you can ask to stop the data collection. Two student workers will stand beside you to prevent you from potentially losing your balance. You will be asked to walk naturally; however, if you feel instability during the treadmill walking, you can hold the handrail to help keep your balance.

It is possible that other rare side effects could occur which are not described in this consent form. It is also possible that you could have a side effect that has not occurred before.

What are the possible benefits to you?

You are not expected to get any benefit from being in this research study.

What are the possible benefits to other people?
Information collected in this study might benefit future potential fallers.

What are the alternatives to being in this research study?
Instead of being in this research study, you can choose not to participate.

What will being in this research study cost you?
There is no cost to you to be in this research study.

Will you be paid for being in this research study?
You will not be paid to be in this research study.

Who is paying for this research?
This research is being paid for by grant funds from NASA. UNMC receives money from NASA to conduct this study.

What should you do if you are injured or have a medical problem during this research study?
Your welfare is the main concern of every member of the research team. If you are injured or have a medical problem as a direct result of being in this study, you should immediately contact one of the people listed at the end of this consent form. Emergency medical treatment for this injury or problem will be available at the Nebraska Medical Center. If there is not sufficient time, you should seek care from a local health care provider.

UNMC has no plans to pay for any required treatment or provide other compensation. If you have insurance, your insurance company may or may not pay the costs of medical treatment. If you do not have insurance, or if your insurance company refuses to pay, you will be expected to pay for the medical treatment.

Agreeing to this does not mean you have given up any of your legal rights.

How will information about you be protected?
All necessary steps will be taken to protect your privacy and the confidentiality of your study data. Your identification will be identified with a unique four-digit number that can be cross-referenced to your legal name in a password-secured database. This database is stored in a locked room. A data collection sheet related to you will be shredded and all collected data stored in the database will be deleted if the data is no longer required.

Who will have access to information about you?
By signing this consent form, you are allowing the research team to have access to your research data. The research team includes the investigators listed on this consent form and other personnel involved in this specific study at UNMC.

Your research data will be used only for the purpose(s) described in the section "What is the reason for doing this research study?"

You are also allowing the research team to share your research data, as necessary, with other people or groups listed below:

- The UNMC Institutional Review Board (IRB)
- Institutional officials designated by the UNMC IRB

Federal law requires that your information may be shared with these groups:

- The HHS Office for Human Research Protections (OHRP)
- NASA

You are authorizing us to use and disclose your research data for as long as the research study is being conducted and at least 7 years after the completion of the research.

You may cancel your authorization for further collection of research data for use in this research at any time by contacting the principal investigator in writing. However, the information which is included in the research data obtained to date may still be used. If you cancel this authorization, you will no longer be able to participate in this research.

How will results of the research be made available to you during and after the study is finished?
In most cases, the results of the research can be made available to you when the study is completed, and all the results are analyzed by the investigator or the sponsor of the research. The information from this study may be published in scientific journals or presented at scientific meetings, but your identity will be kept strictly confidential.

If you want the results of the study, contact the Principal Investigator at the phone number given at the end of this form or by writing to the Principal Investigator at the following address: 984420 Nebraska Medical Center, Omaha NE 68198-4420.

What will happen if you decide not to be in this research study?
You can decide not to be in this research study. Deciding not to be in this research

will not affect your relationship with the investigator or UNMC. You will not lose any benefits to which you are entitled.

What will happen if you decide to stop participating once you start?
You can stop participating in this research (withdraw) at any time by contacting the Principal Investigator or any of the research staff. Deciding to withdraw will otherwise not affect your care or your relationship with the investigator or UNMC. You will not lose any benefits to which you are entitled. Any research data obtained to date may still be used in the research.

Will you be given any important information during the study?
You will be informed promptly if the research team gets any new information during this research study that may affect whether you would want to continue being in the study.

What should you do if you have any questions about the study?
You have been given a copy of "What Do I Need to Know Before Being in a Research Study?" If you have any questions at any time about this study, you should contact the Principal Investigator or any of the study personnel listed on this consent form or any other documents that you have been given.

What are your rights as a research subject?
You have rights as a research subject. These rights have been explained in this consent form and in The Rights of Research Subjects that you have been given. If you have any questions concerning your rights, or want to discuss problems, concerns, obtain information or offer input, or make a complaint about the research, you can contact any of the following:

- The investigator or other study personnel
- Institutional Review Board (IRB)
    - Telephone: (402) 559-6463
    - Email: IRBORA@unmc.edu
    - Mail: UNMC Institutional Review Board, 987830 Nebraska Medical Center, Omaha, NE 68198-7830
- Research Subject Advocate
    - Telephone: (402) 559-6941
    - Email: unmcrsa@unmc.edu

Documentation of informed consent
You are freely making a decision whether to be in this research study. Signing this

form means that:

- You have read and understood this consent form.
- You have had the consent form explained to you.
- You have been given a copy of The Rights of Research Subjects
- You have had your questions answered.
- You have decided to be in the research study.
- If you have any questions during the study, you have been directed to talk to one of the investigators listed below on this consent form.
- You will be given a signed and dated copy of this consent form to keep.

Signature of Subject ___________________________ Date ___________

My signature certifies that all the elements of informed consent described on this consent form have been explained fully to the subject. In my judgment, the subject possesses the legal capacity to give informed consent to participate in this research and is voluntarily and knowingly giving informed consent to participate.

Signature of Person obtaining consent ___________________________ Date ___________

Authorized Study Personnel
Principal

* Chien, Jung
phone: 402-559-5052
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degree: PhD

Secondary

* Siu, Ka-Chun (Joseph)
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* Wang, Zhuo

* Zhang, Yuhang

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degree: BS

Institutional Review Board (IRB)

What Do I Need To Know Before Being In A Research Study?

You have been invited to be in a **research study**. Research studies are also called "research surveys", "research questionnaires" or "scientific protocols." **Research** is an organized plan designed to get new knowledge about health, disease, behaviors, attitudes and interactions of, among and between individuals, groups and cultures. The people who are in the research are called **research subjects**. The **investigator** is the person who is running the research study. You will get information from the investigator and the research team, and then you will be asked to give your **consent** to be in the research.

This sheet will help you think of questions to ask the investigator or his/her staff. You should know all these answers before you decide about being in the research.

What is the **purpose** of the research? Why is the investigator doing the research?

What are the **risks** of the research? What bad things could happen?

What are the possible **benefits** of the research? How might this help me?

How is the research different than what will happen if I m not in the research?

Will being in the research **cost** me anything extra?

Do I have to be in this research study? How will it affect my status at the institution if I say **no**?

Can I **stop** being in the research once I ve started? How?

Who will look at my **records**?

How do I reach the investigator if I have more **questions**?

Who do I call if I have questions about being a **research subject**?

Make sure all your questions are answered before you decide whether or not to be in this research.

Academic Research & Services Building 3000 / 987830 Nebraska Medical Center / Omaha NE 68198-7830
402-559-6463 / FAX 402-559-3300 / Email: irbora@unmc.edu / http://www.unmc.edu/irb

THE RIGHTS OF RESEARCH SUBJECTS
AS A RESEARCH SUBJECT YOU HAVE THE RIGHT

to be told everything you need to know about the research before you are asked to decide whether or not to take part in the research study. The research will be explained to you in a way that assures you understand enough to decide whether or not to take part.

to freely decide whether or not to take part in the research.

to decide not to be in the research, or to stop participating in the research at any time. This will not affect your medical care or your relationship with the investigator or the Nebraska Medical Center. Your doctor will still take care of you.

to ask questions about the research at any time. The investigator will answer your questions honestly and completely.

to know that your safety and welfare will always come first. The investigator will display the highest possible degree of skill and care throughout this research. Any risks or discomforts will be minimized as much as possible.

to privacy and confidentiality. The investigator will treat information about you carefully, and will respect your privacy.

... to keep all the legal rights you have now. You are not giving up any of your legal rights by taking part in this research study.

to be treated with dignity and respect at all times

The Institutional Review Board is responsible for assuring that your rights and welfare are protected. If you have any questions about your rights, contact the Institutional Review Board at (402) 559-6463.