COMPARING GAIT BETWEEN OUTDOORS AND INSIDE A LABORATORY

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ABSTRACT

Gait biomechanics have been studied extensively. Many existing studies, though, have been performed in a controlled laboratory setting, and assumed that measures obtained are representative of gait in a naturalistic environment (e.g., outdoors). Several environmental and psychological factors may contribute to differences between these environments, and identifying any such differences is important for generalizing results outside the laboratory. The purpose of this study was to test the implicit assumption that gait inside a research laboratory does not differ from gait outdoors, when a participant is unaware of data collection in the latter. Means and interquartile ranges (IQR) of several spatio-temporal and kinematic gait characteristics were obtained from 19 young adults during several gait conditions both inside a laboratory environment and outdoors. Four comparisons were made between the two environments, including conditions involving: 1) self-selected speeds, 2) matching outdoors self-selected speeds, 3) matching outdoors self-selected speeds while carrying a crate, and 4) matching outdoors hurried speeds. Spatio-temporal variables differed between the two environments in that self-selected walking speed was 1.7% slower inside the lab and cadence was 1.4-2.6% lower for all four comparisons. At heel contact, the foot was 4.4-8.1% more dorsiflexed inside the lab for all comparisons except in matching hurried outdoors walking speed. Minimum toe clearance was 6.5-16.2% lower outdoors for all four comparisons. It is unclear if these differences impair the ability to generalize gait study results to outside the laboratory. Nevertheless, some specific differences exist in gait between environments, and that research should recognize.

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CHAPTER 1 – OVERVIEW

Gait biomechanics is a broadly studied area of clinical research. Many experiments within this field are performed within a research laboratory, and operate under the implicit assumption that gait within the laboratory is similar to gait in a naturalistic setting. Past work reveals that several factors could alter gait within the laboratory, specifically environmental factors and psychological factors. Identifying any gait differences between the two environments would be important for generalizing results from laboratory gait studies to outdoors.

This thesis discusses research aimed at testing the implicit assumption that gait within the laboratory is not different from gait in a representational outdoors setting. Chapter two provides an overview of gait biomechanics research, describes factors that contribute to gait differences, and summarizes the design of the study. Chapter three is a self-contained manuscript describing all facets of the project and will be submitted for publication.

CHAPTER 2 – INTRODUCTION

OVERVIEW OF GAIT BIOMECHANICS RESEARCH

Gait biomechanics have been studied extensively. According to a Medline keyword search of “gait”, 16,395 studies were published from 2000 through 2010. These studies can be broadly categorized into three groups according to their goals and design (Portney & Watkins, 2000). First, descriptive studies describe characteristics of selected populations (Blin et al., 1990; Berg et al., 1997; Powers et al., 1999; Mcgraw et al., 2000). Second, exploratory studies explore relationships between various aspects of gait (Kirtley et al., 1985; Collins & Wittle, 1989; Pavol et al., 1999; England and Granata, 2007). Third, experimental studies experimentally manipulate independent variables and assess the effects on selected dependent variables to begin to discern cause and effect (Redfern & Dipasquale, 1997; Lay et al., 2006; Azevedo et al., 2014). A large number of these studies are conducted in research laboratories, and operate with the implicit assumption that gait inside a research laboratory does not differ from gait in a more naturalistic setting, such as outdoors. Ideally, gait inside the laboratory will be identical to gait outside the laboratory in order to maximize generalizability to the “real world”.

FACTORS THAT CONTRIBUTE TO GAIT DIFFERENCES

Many factors could play a role in altering gait kinematics between outdoors and inside a laboratory. These factors can be categorized as environmental, psychological, personal, and task-related. Environmental factors include the physical components of the gait setting (e.g. lighting, surface characteristics, and sound). Psychological factors refer to elements that alter participant attention and awareness (e.g. Hawthorne effect and demand characteristics). Personal factors refer to the subject-specific elements of a participant (e.g. age and occupation). Task-related factors include activities performed during gait (e.g. manual materials handling and dual-task activities).

Environmental Factors

Several environmental factors could contribute to possible differences in gait between inside a laboratory and outdoors. For example, laboratory walkways are traditionally well-lit, flat, obstruction-free, and covered with painted plywood (Myung & Smith, 1997; Lockhart et al., 2002; Cham & Redfern, 2002), vinyl (Myung & Smith, 1997; Brady el al., 2000; Cham & Redfern, 2002; Lockhart et al., 2007), carpet (Brady et al., 2000), stainless steel (Grönqvist et al., 1993; Myung & Smith, 1997; Lockhart et al., 2002), or ceramic tile (Myung & Smith, 1997; Lockhart et al., 2002). However, environmental factors outdoors can be highly unpredictable. Four environmental factors that contribute to gait differences include lighting, visual flow, surface conditions, and sound.

Lighting has been shown to affect gait, visual orientation, and safety perception. Some examples include findings that depth perception and distant-edge-contrast are important for maintaining balance and navigating obstacles (Lord & Dayhew, 2001), brightness and flooring color alters safety perception (Zamora et al., 2008), reducing and altering brightness affects gait parameters and their variability (Figueiro et al., 2011), and illumination and wall-edge emphasis aid in visual orientation while walking (Itoh, 2006). Itoh (2006) found that walking in lower levels of illumination reduced cadence in both elderly and young participants. A prospective study by Lord and Dayhew (2001) found impaired vision to be an important risk factor for falls, and found that adequate depth perception and distant-edge-contrast aid in maintaining balance and navigating obstacles.

Visual flow refers to the displacement of landmarks within the visual field during gait, and can induce changes in spatio-temporal gait parameters. For example, Pailhous et al. (1990) had participants walk at a “lively” speed, while luminous spots on the floor did not move, moved in the opposite direction of travel, and moved in the same direction of travel. When the luminous spots moved in the opposite direction of travel, participants decreased walking speed, decreased cadence, and decreased stride length. When the luminous spots moved in the same direction of travel, participants increased cadence and decreased stride length. Additionally, Mohler et al. (2007) showed that perceived flow speed impacts self-selected walking speed, the run/walk transition speed, and the walk/run transition speed. When perceived flow speed was faster than actual walking speed, self-selected walking speeds were slower, and run/walk and walk/run transition speeds were slower. Lastly, Graci et al. (2009) showed that limiting visual flow via circumferential occlusion of the visual field induced slower walking speeds and shorter step lengths.

Surface conditions have been shown to affect gait. Past work reveals that surface height irregularities alters stepping parameters and their variability (Thies et al., 2005; Schulz, 2011; Menant et al., 2009), multi-surface terrain induces higher gait variability (Marigold & Patla, 2008), surface stiffness alters required mechanical work but has little effect on kinematics (Lejeune et al., 1998), and surface friction affects slip-related gait parameters (Cham & Redfern, 2002; Dickson & Roethlisberger, 2003). For example, Shulz (2011) examined gait alterations in the presence of surface height irregularities (right triangular prisms, ~13mm high, random configuration). With respect to walking without obstacles, minimum toe clearance was 2.0 times higher when obstacles were made visible and 2.5 times higher when the obstacles were hidden. Also, Cham and Redfern (2002) investigated gait changes during walking on smooth (vinyl) and rough (painted plywood with impregnated silicate) surfaces at various angles (0°, 5°, and 10°). They reported a 0.01-0.02 increase in the required coefficient of friction (RCOF), a 0-0.7 deg greater dorsiflexion at heel contact, and a 1-17 deg/s increase in foot angular velocity at heel contact when walking over a textured surface compared to a smooth surface.

Sound can vary between environments, and contributes to altering gait. Auditory stimuli have been used to manipulate gait patterns, specifically gait variability (Kaipust et al., 2013), and has been used in gait rehabilitation and training (Veteto, 2013; Hove et al., 2012). For example, Kaipust et al. (2013) manipulated gait variability of kinematics parameters, such as stride frequency, stride length, and stride width, using auditory stimuli, including white noise, a metronome, and chaotic rhythm. Parkinson's disease leads to movement timing disruptions (Grahn & Brett, 2009) and can lead to instability and falls (Balash et al., 2005). Hove et al. (2012) analyzed gait in Parkinson's patients during rhythmic auditory stimulation and interactive feedback of participant step timing. Their results indicated that this technique could be used as a therapeutic tool to lower cadence variability and improve walking stability.

Psychological Factors

Psychological factors have been shown to affect clinical research. Several studies have indicated the presence of an intrinsic central pattern generator for human gait motor control that adapts and can be selectively modified (Calancie et al., 1994; Choi & Bastian, 2007); however, gait is not independent of attention and awareness (Yogev-Seligmann et al., 2008).

Two psychological factors that could contribute to gait differences include participant awareness of the research investigation and safety perception.

Participant awareness of the research data collection and objective has the potential to affect gait. For instance, the so-called “Hawthorne effect”, or behavioral improvement when research subjects “know or believe that they are being evaluated by an observer” (Berthelot et al., 2011), was coined after a series of social science experiments aimed at examining how physical conditions within a work place affected worker satisfaction and performance (Dickson & Roethlisberger, 2003; Mayo, 2013). Improvements were observed under all working conditions, even in the case of an unchanged working condition, thus suggesting that factors, such as morale, milieu, supervision, group influences, or researcher response, may alter a research subject’s behavior (Parsons, 1974; Mayo, 2013). Past work in clinical research have observed improvements in response variables as a result of participant awareness, such as enhanced cognitive function after more extensive follow-up in dementia patients (McCarney et al., 2007), and better well-being and reduced pain post-operation in patients aware of the study (De Amici et al., 2000). Also, demand characteristics, or “cues in the experimental setting that allow subjects to infer how they are expected to behave” (Weber and Cook, 1972), are related to the Hawthorne Effect and could alter gait within the laboratory. Weber and Cook (1972) described four roles that participants may adopt when influenced by demand characteristics: 1) good subject (attempts to affirm researchers hypothesis), 2) faithful subject (scrupulously follows protocol), 3) negativistic subject (attempts to disprove researchers hypothesis), and 4) apprehensive subject (concerned with evaluation and attempts to portray themselves favorably). To our knowledge, the degree to which gait is affected by psychological factors is unknown, despite the Hawthorne effect having been controlled for in past gait research (Wang et al., 2009; Dunsky et al., 2008).

Safety perception is environmental-dependent (Zamora et al., 2008) and is a known effector of gait (Heiden et al., 2006; Menant et al., 2009; Cham & Redfern, 2002). A study by Zamora et al. (2008) investigated how pavement design affected safety perception in the elderly. They conducted the study by showing participants images of various pavement environments with differing texture, joint presence (e.g. an expansion joint in a sidewalk), lighting, and color, and asking them to order images in order of safety perception. Texture was found to be the most important factor, and participant living environment was found to influence the relative importance of factors. Cham and Redfern (2002) examined changes in gait while participants walked under varying floor conditions. The trial types included 1) baseline (knew floor was dry), 2) anticipation (uncertain of slippery contaminant presence), and 3) recovery (knew floor was dry but had experience a slip). With respect to the baseline trials, participants executed 16-33% a lower required coefficient of friction peak (RCOF) during anticipation trials and 5-12% lower RCOF during recovery trials. These alterations in RCOF were associated with a reduced stride length, foot angle at heel contact, and foot angular velocity at heel contact, and effectively reduce the risk of slipping. These studies indicate how safety perception varies between environments, and how uncertain environmental conditions can affect gait.

Personal Factors

Personal factors can also contribute to differences in gait. Some examples include age (Itoh, 2006), obesity (Browning et al., 2006; Browning & Kram, 2007), occupation (Rietdyk & Rhea, 2011), medical conditions (Mueller et al.,1994; Katoulis et al., 1997), and shoe characteristics (Menant et al., 2009). The elderly demographic has been heavily studied due to a growing population and a higher propensity for falling (Tideiksaar, 1989; Vincent & Velkoff, 2010), specifically slips and trips account for approximately 60% (Berg et al., 1997) of falls in the elderly population. Elble et al. (1991) looked at several gait kinematics in young and elderly participants and found no significant difference in minimum toe clearance, which indicates that tripping accidents within this demographic may not be due to a higher propensity for striking an obstacle. The obese population has a higher propensity for falling (Fjeldstad et al., 2008), and has been the topic of past gait studies (Browning et al., 2006; Browning & Kram, 2007;Lai et al, 2008). Lai et al (2008) performed a study that revealed several spatio-temporal differences, including slower walking speeds, short stride lengths, and greater stance time. In industrial settings, slips, trips, and falls accidents, while walking on a level surface, have been frequently cited as a cause of injury (Braddee et al, 2000; Swaen et al., 2014; Lipscomb et al., 2006), and it has been hypothesized that worker experience may translate into a decreased risk of tripping (Rietdyk & Rhea, 2011). Rietdyk & Rhea (2011) examined how toe clearance differs between construction workers and a gender-matched control group, while walking over obstacles. Construction workers showed greater sensory-to-motor control by decreasing lead toe clearance variability, decreasing trailing toe clearance variability, and by better scaling of trailing toe height as it crossed over the obstacles. Diabetic neuropathy is a medical condition characterized by nerve damage throughout the body. Studies by Mueller et al. (1994) indicated that patients with diabetic foot ulcers showed spatio-temporal gait differences, lower ankle mobility, moment, and power. Katoulis et al. (1997) revealed that individuals with diabetic neuropathy shifted center of pressure over the stance limb during walking, which could induce more stress to the plantar surface and potentially induce foot ulcers. Menant et al. (2008) examined the effects of shoe type on gait characteristics and found that an elevated heel and softer sole impairs walking stability, while a higher collar height and medium hardness sole offered greatest walking stability

Task-Related Factors

Task-related factors have also been shown to influence gait patterns. These tasks include manual material handling (Marigold & Patla, 2008), hurried walking (Grieve, 1983), dual-task activities (Ebersbach et al., 1995), and fatigue (Yoshino et al., 2004). Manual material handling, such as carrying an object in front of the body, is a common industrial task and leads to an impeded the lower visual field, which affects stepping parameters and their variability in multi-surface environments (Ebersbach et al., 1995; Rhea & Rietdyk, 2007). Azevedo et al. (2014) investigated the effects of materials handling position and load weight on mean heel and toe clearance. Their results showed that increasing load weight lowered mean heel and toe clearance, leading to an increased risk of tripping, and that changing materials handling position showed no significant effect. Hurried walking alters gait and increases risk of slipping (Grieve, 1983; Redfern et al., 2001;Cham & Redfern, 2002) and tripping (Pavol et al., 2001). Despite Schulz (2011) finding an increase in minimum toe clearance during hurried walking, Pavol et al. (2001) found an increased likelihood of tripping with increasing walking speed, which suggests a lower likelihood of striking an obstacle but higher risk of falling from striking an obstacle. Fatigue from prolonged walking has been associated with gait changes (Yoshino et al., 2004). Yoshino et al. (2004) investigated the effect of fatigue on gait in a 3-hour walking study, and found that fatigue in the tibialis anterior leads to gait instability, and is compensated for by decreasing cadence in order to enhance local dynamic stability. Dual-task activities, such as cell phone use, are common to the outdoors environment and play a role in altering gait kinematics

(Ebersbach et al., 1995; Springer et al., 2006; Lamberg & Muratori, 2012; Nasar et al., 2008). Lamberg and Muratori (2012) investigated the effects of cell phone use on gait kinematics, and found that individuals texting or talking on the phone tended to walk slower and laterally deviate from their intended walking direction.

SUMMARY AND PURPOSE

The purpose of the study described in this thesis was to test the implicit assumption that gait within a research laboratory does not differ from gait outdoors. The experimental design described below includes differences in both environmental and psychological factors between these two environments. As such, they will be the focus of this investigation. Any differences in gait between these two environments would be important to recognize when generalizing results from laboratory gait studies to outdoors.

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CHAPTER 3 – COMPARING GAIT BETWEEN OUTDOORS AND INSIDE A LABORATORY

INTRODUCTION

Human gait is widely studied in research laboratories. A Medline database keyword search for “gait” revealed that an average of 1,490 publications were produced annually between the years 2000-2010. These gait studies can be broadly categorized (Portney & Watkins, 2000) as 1) descriptive in that they describe characteristics of selected populations (Blin et al., 1990; Berg et al., 1997; Powers et al., 1999; Mcgraw et al., 2000), 2) exploratory in that they explore relationships between various aspects of gait (Kirtley et al., 1985; Collins & Wittle, 1989; Pavol et al., 1999; England and Granata, 2007), and 3) experimental in that they experimentally manipulate independent variables and assess the effects on selected dependent variables to begin to discern cause and effect (Redfern & Dipasquale, 1997; Lay et al., 2006; Azevedo et al., 2014). All three types of studies are valuable and important to the overall research endeavor. Many of these gait studies are conducted inside a research laboratory, and operate with the implicit assumption that gait inside a research laboratory does not differ from gait in a more naturalistic setting, such as outdoors.

Several environmental factors could contribute to differences in gait between inside a laboratory and outdoors. For example, walkways in laboratories are traditionally flat, obstruction-free, and covered with plywood (Myung & Smith, 1997; Lockhart et al., 2002; Cham & Redfern, 2002), vinyl (Myung & Smith, 1997; Brady el al., 2000; Cham & Redfern, 2002; Lockhart et al., 2007), carpet (Brady et al., 2000), stainless steel (Grönqvist et al., 1993; Myung

& Smith, 1997; Lockhart et al., 2002), or ceramic tile (Myung & Smith, 1997; Lockhart et al., 2002). Walking surfaces outdoors commonly involve different materials (e.g. pavement, earth) and have different surface characteristics that have been shown to affect gait parameters and their variability. Some of these characteristics include surface height irregularities (Thies et al., 2005; Menant et al., 2009; Schulz, 2011), multi-surface terrain (Marigold and Patla, 2008), surface stiffness (Lejeune et al., 1998), and surface friction (Myung & Smith, 1997; Cham & Redfern, 2002). Schulz (2011) reported the presence of surface height irregularities (right triangular prisms, ~13mm high, random configuration) increased minimum toe clearance 2-2.5 times higher than without surface irregularities. Cham and Redfern (2002) reported a 0.01-0.02 increase in the required coefficient of friction (RCOF), a 0-0.7 deg greater dorsiflexion at heel contact, and a 1-17 deg/s increase in foot angular velocity at heel contact when walking over a textured surface compared to a smooth surface. In addition to ground surface characteristics, lighting (Lord & Dayhew,2001; Itoh, 2006; Figueiro et al, 2011), visual flow (Pailhous et al., 1990; Mohler et al., 2007; Graci et al., 2009), and sound (Kaipus et al., 2013) have also been found to elicit changes in gait. Kaipust et al. (2013), for example, were able to manipulate gait kinematics variability, such as stride frequency, stride length, and stride width, using auditory stimuli, including white noise, a metronome, and chaotic rhythm.

Another factor that could contribute to differences in gait between inside a laboratory and outdoors is the so-called “Hawthorne effect”. The Hawthorne effect is the occurrence of behavioral improvement when research subjects “know or believe that they are being evaluated by an observer” (Berthelot et al., 2011), and dates back to a series of social science experiments aimed at examining how physical conditions within a work place affected worker satisfaction and performance (Dickson & Roethlisberger, 2003; Mayo, 2013). During gait studies, it is possible that research volunteers unintentionally alter their gait when they are aware that they are being watched and/or measurements are being collected. Also, demand characteristics, or "cues in the experimental setting that allow subjects to infer how they are expected to behave" (Weber and Cook, 1972), can be considered within the Hawthorne Effect, and could alter gait within the laboratory.

The purpose of this study was to test the implicit assumption that gait within a research laboratory does not differ from gait outdoors. Gait was characterized using common spatio-temporal measures as well as gait characteristics related to risk of tripping and slipping. It was hypothesized that mean and variability of gait measures would not differ between the two environments. Any differences between the two environments would be important to recognize when generalizing results from laboratory gait studies to outdoors.

METHODS

Nineteen young adults (age 21.7±1.8 years, BMI<28) were recruited from the university population, including nine males and ten females. None of the participants had any self-reported medical conditions that altered gait. The university Institutional Review Board approved this study, and written informed consent was provided prior to participation.

The experimental protocol had a 1-1.5 hour duration and required participants to walk under a total of seven experimental conditions. The first three conditions were performed outdoors, and the next four were performed inside a research laboratory. Participants wore their own athletic shoes and clothing in order to eliminate any unintended deviation from natural gait patterns due to unfamiliar attire (Menant et al., 2009). Prior to the session, each participant was told that they were not at any risk of being slipped or tripped, to avoid potential effects on gait in either or both environments (Cham & Redfern, 2002; Heiden et al., 2006).

At the beginning of the experiment, participants were told three important aspects of the study. First, the purpose of the study was to analyze the effects of warm-up on gait, but because the lab's treadmill was not working properly, the warm-up would take place outdoors. Second, gait would be measured immediately after warm-up in the research laboratory. Third, an inertial measurement unit system (Xsens Technologies, Enschede, The Netherlands) would be used to measure gait, and that it needed to be donned prior to going outdoors to minimize the time between the end of warm-up and the start of measurements inside the laboratory. In reality, the system was donned prior to going outdoors so that gait measurements could be collected outdoors. As such, any differences in gait between outdoors and inside the laboratory could be due to not only environmental differences, but also the awareness of being tested (i.e. Hawthorne Effect).

The first three conditions were performed outdoors on a 1-meter wide, 10.8-meter-long concrete sidewalk area designated using cones (Figure 1). The sidewalk was segmented every 1.8 meters by expansion joints, and each segment area was flat ($<0.5^{o}$, measured using an inclinometer). For the self-selected condition, participants were instructed to walk at their natural walking speed. Carrying a crate was investigated because load carriage is an occupational-related task that impedes the lower visual field, can alter gait, and can increase risk of falling (Lipscomb et al., 2006; Azevedo et al., 2014; Swaen et al., 2014). For the crate condition, participants were instructed to walk at a natural walking speed while carrying a 6.8 kg crate in front of the body with elbows flexed ~90 degrees. A hurried speed condition was performed, because gait speed has been shown to increase risk of slipping (Grieve, 1983; Redfern et al., 2001;Cham & Redfern, 2002) and tripping (Pavol et al., 2001). For the hurried condition, participants were instructed to walk as if they were in a rush between meetings or classes. If their speed was less than 1.6m/s, the trial was discarded and the participant was asked to walk faster. The average speed for this condition was determined by measuring the time it took participants to walk 7.2 m as indicated by natural markings on the sidewalk. For all three of these conditions, participants were instructed to walk back-and-forth continuously between the ends of the walkway area until indicated by the investigator to stop. A research assistant posing as an uninvolved student working on a laptop was positioned nearby to collect data from the inertial measurement unit system wirelessly. The experiment was only conducted when weather was accommodating (i.e. mild temperatures, no precipitation, and dry ground).

The next four conditions were performed in a research laboratory on a 1.5-meter-wide, 10-meter-long walkway covered in vinyl tiles (Figure 1). The four conditions were: 1) self-selected speed, 2) matching the self-selected speed from outdoors, 3) matching the self-selected speed from outdoors while carrying a crate, and 4) matching hurried speed from outdoors. Speed was measured inside using a Vicon MX-T10 six-camera motion analysis system (Vicon Motion Systems Inc., LA, CA) with a marker on the right acromion. For the matching speeds, the participants were given feedback if their speed deviated substantially (within ±10.0cm/s) from the outside average speed of the respective walking condition. The participants were told to maintain a consistent speed unless otherwise directed. The participants were asked to walk to the end of the walkway at a consistent speed, while gazing at a target at the end of the walkway, then stop and wait for further instruction. The participants were made aware that gait measurements were being obtained during the inside walking trials.

Figure 1: Participant's perspective of the walking surface outdoors (Left) and inside the laboratory (Right).

Lower limb kinematics were measured during all walking conditions using the inertial measurement unit system. Sensors were worn on the feet, shank, thigh, and pelvis, but only the sensors on the feet were used to calculate our dependent variables. Flexible cohesive bandaging (CoFlex, Salisbury, MA) was used, in addition to the sensor straps, to ensure no motion of the sensors relative to the body. Data were sampled wirelessly at 120Hz via a Bluetooth receiver and a laptop with the system's accompanying software (Xsens MVN Studio, Xsens Technologies, Enschede, Netherlands). This software calculates segment orientation using segment dimensions, an initial calibration procedure that requires the participant to move through several specified body positions, and a sensor fusion algorithm. This fusion algorithm corrects for orientation integration error using the perceived direction of gravity from the accelerometer and the direction of magnetic north (Luinge & Veltink, 2004; Roetenberg et al., 2007). According to the manufacturer, the accuracy of the computed orientation is within 2 degrees RMS. Raw linear acceleration, raw angular velocity, and the software's computed segment and sensor orientation were exported for processing in Matlab (The Mathworks Inc., Natick, MA) to determine our dependent variables.

Calculating the dependent variables required some manipulation of the raw accelerometer and gyroscope data. The raw accelerometer and gyroscope data were filtered using a 2^{nd} order low-pass Butterworth filter with a cutoff frequency of 17Hz (Schepers et al., 2007; Mariani el al., 2010; Mariani el al., 2012;), and the acceleration due to gravity was removed from the vertical acceleration component. The software outputs quaternion vectors to describe the sensor orientation relative to the global reference frame, which were placed in a rotation matrix to convert gyroscope and accelerometer data into the global reference frame. Three events including heel-contact, toe-off, and flat-foot, were calculated for each gait cycle using previously derived methods (Sabatini et al., 2005; Jasiewicz et al., 2006; Mariani el al., 2012). Heel-contact was identified as the instant of peak angular velocity near maximum dorsiflexion angle, toe-off was identified as the instant of peak angular velocity near maximum plantar flexion angle, and flat-foot was identified by the minimum absolute value of angular velocity between heel-contact and toe-off. The data were divided up by gait cycle, or right heel-contact to right heel-contact, and each dependent variable was determined for each gait cycle.

Three spatio-temporal characteristics of gait were found including cadence, stride length, and average walking speed. Cadence was calculated for each gait cycle using the time difference between a given right heel-contact to the following right heel-contact. Stride length was calculated for each gait cycle using a modified version of the technique reported by Sabatini et al (Sabatini et al., 2005). This method involved numerically integrating the sensor horizontal acceleration from flat-foot to flat-foot, with linear de-drifting of the horizontal velocity using the assumption of zero velocity at flat-foot. For each walk along the outdoors and laboratory walking space, walking speed for each gait cycle was calculated as the average of right and left stride lengths divided by the time differences in flat-foot.

It was deemed desirable for within-trial gait speed variability to be low to limit variations in gait speed within a trial from contributing to variability in our dependent variables. For the three outdoors walking conditions and the inside self-selected walking condition, a gait cycle was required to have a walking speed within ±7.5cm/s of the average walking speed of all the gait cycles within that condition. The inside matching speed conditions used the average walking speed of the respective outdoors condition for determining of a successful gait cycle. Only dependent variables that passed this criterion were used in the statistical analyses.

Three additional dependent variables that are associated with slipping and tripping were found. Foot angle at heel contact and foot angular velocity at heel contact have both been correlated with required coefficient of friction, which is associated with the likelihood of slipping and falling (Redfern et al., 2001; Cham & Redfern, 2002; Heiden et al., 2006). Minimum toe clearance was defined as the minimum height of the toe from the ground during the swing phase, and is associated with the likelihood of tripping and falling (Elble et al., 1991; Winter, 1992; Schulz et al., 2010). A modified version of the technique developed by Mariani et al (2012) was used to calculate minimum toe clearance. This method entailed numerical integration of the sensor's vertical acceleration from flat-foot to flat-foot, with linear de-drifting of the vertical velocity and position using the assumption of zero velocity and position at flat-foot. For each gait cycle, the relative locations of the heel and toe with respect to the sensor were calculated using sensor position at heel-contact, sensor position at toe-off, and the measured shoe length. For each subject and gait condition, the means of the calculated dimensions were obtained over all of the gait cycles, and the mean dimensions were then used for all of the gait cycles within that condition.

Four comparisons of interest were made between conditions outdoors and inside the lab. The first comparison was between walking at self-selected speeds. This allowed for a comparison between environments, while participants walked naturally. However, gait speed may have differed between outdoors and inside and confounded any other differences between environments. As such, the second comparison of interest was between outdoors and inside while walking at matching speeds. This comparison used the outdoors self-selected speed condition and the inside matching speed condition. The third comparison of interest was between outdoors and inside while walking at matching hurried speeds. The fourth comparison was between outdoors and inside walking at matching speeds while carrying a crate.

A two-way repeated measures analysis of variance with planned contrasts was used to perform our comparisons of interest. The two independent variables were condition (seven different conditions including three outdoors and four inside) and gait cycle number. Up to 50 gait cycles were included from each participants in each condition. To assess differences in gait variability between outdoors and inside, a one-way repeated measures analysis of variance with planned contrasts was used on the interquartile range (IQR) of each dependent variable to perform our comparisons of interest. The independent variable for this analysis was condition. A minimum of six gait cycles was required from each condition in order to include the participant's interquartile range in this analysis. This resulted in nine values being excluded from this analysis. Analyses were performed with JMP v7 (Cary, North Carolina, USA), and statistical significance was concluded when $p \leq 0.05$.

RESULTS

The first comparison was between walking at a self-selected speed outdoors and walking at a self-selected speed inside the lab. Walking speed was 1.7% slower inside ($p<0.001$), and cadence was 2.0% lower inside ($p<0.001$). Foot angle at heel contact was 4.4% more dorsiflexed inside ($p<0.001$), and minimum toe clearance was 16.2% higher inside ($p<0.001$). IQR of foot angle at heel contact was 21.8% lower inside ($p=0.021$), and IQR of foot angular velocity at heel contact was 30.6% lower inside ($p=0.016$).

The second comparison was between walking at a self-selected speed outdoors and a matching walking speed inside the lab. Although we attempted to match walking speed, walking speed was 0.8% faster inside ($p=0.026$), cadence was 2.0% lower inside ($p<0.001$), and stride length was 1.8% higher inside ($p<0.001$). Foot angle at heel contact was 8.1% more dorsiflexed inside ($p<0.001$), and minimum toe clearance was 13.9% higher inside ($p<0.001$). IQR of foot angle at heel contact was 18.9% lower inside ($p=0.049$), and IQR of foot angular velocity at heel contact was 26.7% lower inside ($p=0.040$).

The third comparison was between walking at a hurried speed outdoors and walking at a matching hurried speed inside the lab. Although we attempted to match hurried walking speeds, walking speed was 3.5% slower inside ($p<0.001$), cadence was 2.6% lower inside ($p<0.001$), and stride length was 1.8% lower inside ($p<0.001$). Foot angular velocity at heel contact was 1.7% lower inside ($p<0.001$), and minimum toe clearance was 14.2% higher inside ($p<0.001$). No differences were observed in IQR of any dependent variables.

The fourth comparison was between walking with a crate at a self-selected speed outdoors and a walking with a crate at a matching speed inside the lab. Cadence was 1.4% lower inside ($p<0.001$), and stride length was 1.8% higher inside ($p<0.001$). Foot angle at heel contact was 4.8% more dorsiflexed *(p*<0.001), and minimum toe clearance was 6.5% higher inside *(*p=0.016). IQR of cadence was 39.4% higher inside (*p*=0.008), and IQR of stride length was 44.5% higher inside (*p*<0.001).

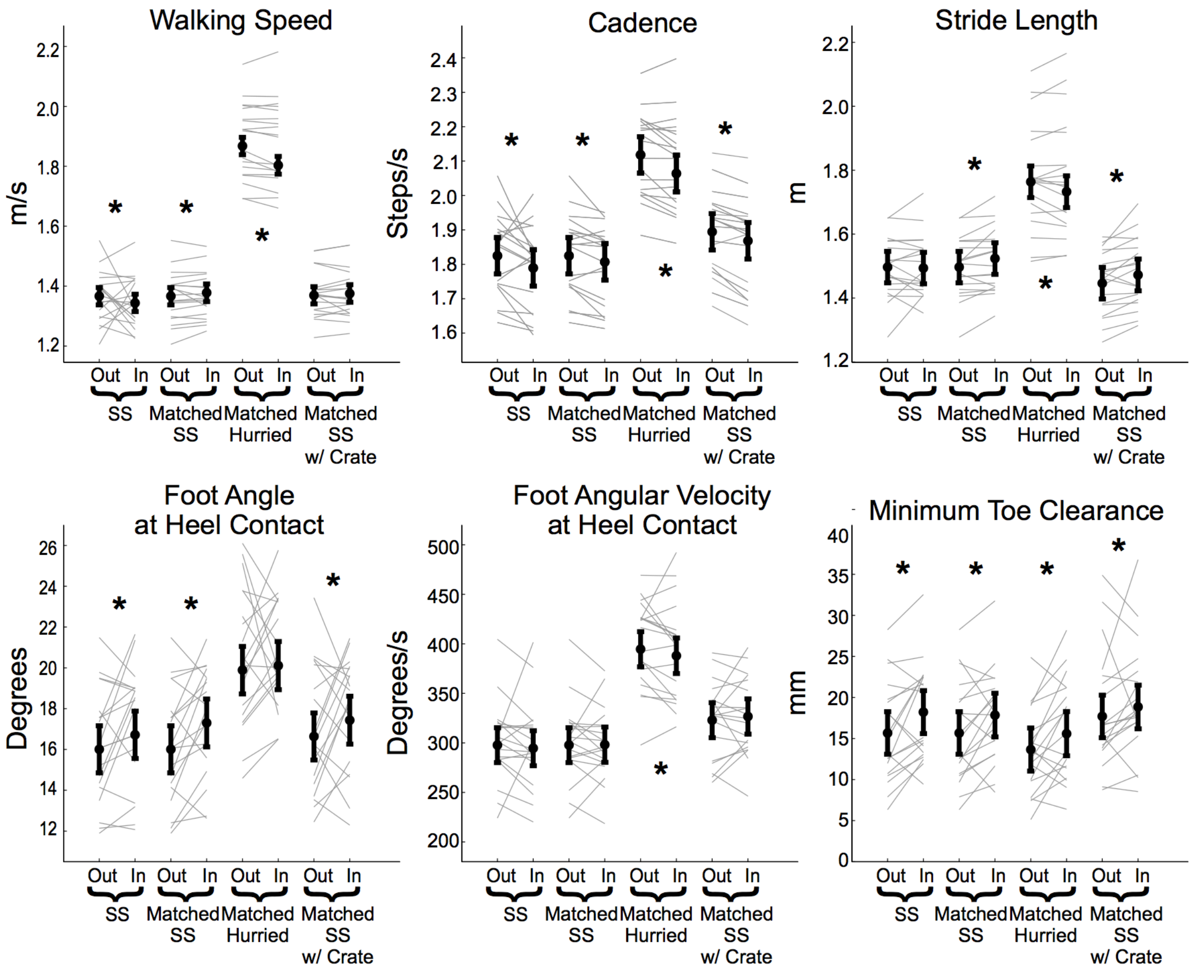

Figure 2: Mean and 95% confidence interval of the mean of gait variables. Comparisons are made between relevant conditions (* statistical difference between conditions). Gray lines represent subject-specific changes. A positive foot angle is in the direction of dorsiflexion. A positive foot angular velocity is in the direction of plantar flexion.

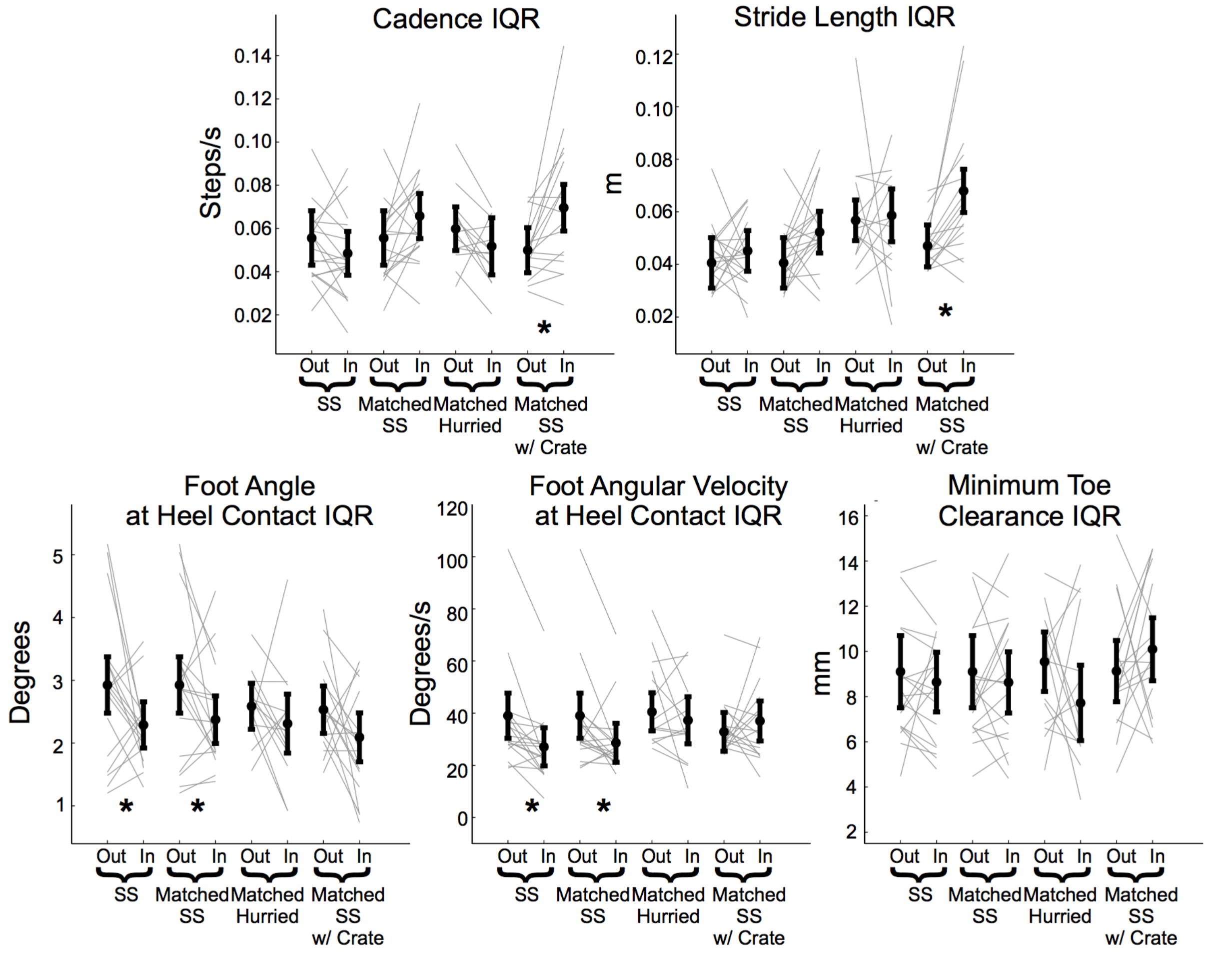

Figure 3: Mean and 95% confidence interval of the IQR of gait variables. Comparisons are made between relevant conditions (* statistical difference between conditions). Gray lines represent subject-specific changes. A positive foot angle is in the direction of dorsiflexion. A positive foot angular velocity is in the direction of plantar flexion.

DISCUSSION

The purpose of this study was to determine how gait differs between outdoors when participants were unaware of gait measurements being collected, and inside a laboratory when participants were aware of measurements being collected. Ideally for gait researchers, no differences would exist. We hypothesized no differences in mean and variability (IQR) of gait characteristics between the two environments. Results showed statistically significant differences in 18 of 24 comparisons of mean values, and 6 of 24 IQR values. As such, we rejected our hypothesis. Gait spatio-temporal characteristics differed between the two environments in that self-selected speed was lower inside the lab, and cadence was lower inside the lab across all four walking conditions. Stride length, however, did not exhibit a consistent difference between the two environments across the four walking conditions. A discussion of the other dependent variables follows.

Some limitations exist within this experiment. First, this study aimed to determine differences in gait between the laboratory and a naturalistic setting, rather than to determine how environment or psychological factors contribute individually to differences. This approach introduces the possibility of compounding or conflicting effects. Second, visual orientation was not controlled for outdoors. Visual feedback via exteroception (information regarding environmental characteristics) and exproprioception (information regarding relation of body segments to the environment) has been found to influence gait (Patla, 1998; Rhea & Rietdyk, 2007; Pailhous et al., 1990; Mohler et al., 2007; Graci et al., 2009). Third, the outdoors environment presents one specific walking scenario. In reality, outdoors environments can take place on a variety of surfaces with a range of factors affecting gait. Fourth, the researcher was not completely removed from the outside data collection space. Although the participant was not made aware of the data collection, it is possible that the presence of the research may have led to gait alterations. Fifth, only college-aged participants were used in this study. Any changes observed between the two environments may be dependent on age, occupation, demographic, or past experience in gait laboratories.

Slip-related measures differed between environments. Foot angle at heel contact was more dorsiflexed inside the lab during three out of four walking conditions, and foot angular velocity at heel contact was slower inside the lab for the hurried condition. A more dorsiflexed foot at heel contact suggests a higher risk of slipping inside the lab (Redfern et al., 2001; Cham & Redfern, 2002; Heiden et al., 2006). This difference may have resulted from a longer stride length inside the lab. It is also possible that the Hawthorne effect enhanced these differences. For instance, the Hawthorne effect may induce more exaggerated gait kinematics, such as greater dorsiflexion at heel contact. Cham and Radfern (2002) reported a similar change in foot angle at heel contact magnitude, which corresponded to a 0.01 increase in RCOF. RCOF has been used in conjunction with dynamic coefficient of friction (DCOF), which is frequently used to assess available friction between the shoe-floor interfaces (Myung & Smith, 1997; Hanson et al., 1999). For reference, past studies have reported DCOF for PVC-soled shoes and ceramic (Myung & Smith, 1997), steel (Myung & Smith, 1997), VCT (Hanson et al., 1999), and carpet (Hanson et al., 1999) flooring to be 0.57, 0.27, 1.12, and 1.43, respectively. Hanson et al. (1999) created a logistic regression model to predict risk of slipping from the differences between DCOF and RCOF. Using their model and assuming a worst case-scenario (DCOF - RCOF = 0.16 ± 0.005), a 0.01 increase in RCOF would translate to a maximum of 3% increase in risk of slipping. A slower foot angular velocity at heel contact suggests a lower risk of slipping inside the lab. This change was only observed for the hurried walking condition, and may have been induced by the small decrease in walking speed inside the lab.

Minimum toe clearance was higher inside the lab for all four walking conditions, suggesting a lower risk of tripping inside the lab (Elble et al., 1991; Winter, 1992; Schulz et al., 2010). Several factors may have contributed to these differences. First, participants were not given instruction on where to look outdoors, which may have yielded visual feedback in the form of exteroception and exproprioception. Past studies have found these factors to be important for obstacle avoidance, and led to a lower minimum toe clearance during walking over obstacles (Patla, 1998; Rhea & Rietdyk, 2007). Enhanced visual feedback outdoors may have effectively lowered minimum toe clearance. Second, an increased minimum toe clearance may be a result of the Hawthorne effect. For instance, participants may execute a more cautious gait or may exaggerate gait kinematics inside the laboratory by increasing minimum toe clearance.

Gait variability also differed between environments. For the self-selected walking speed and matching self-selected walking speed conditions, IQR of foot angle at heel contact, and IQR of foot angular velocity at heel contact were both lower inside the lab. A more consistent, predictable surface inside the laboratory may have led to lower gait variability. Also, this decrease in variability may be due to the Hawthorne effect in that awareness of being tested may induce more consistent gait patterns in an effort to improve performance. However, a decrease in IQR inside the laboratory for other variables and conditions was not observed, which may suggest that these are not relevant factors or that confounding factors may be present. For the crate carrying conditions, IQR of cadence and IQR of stride length were higher inside the lab. Walking was performed continuously outdoors, rather than awaiting instructions at the end of the walkway, and participants had freedom to change their gaze outdoors, which may have contributed to lower spatio-temporal variability outdoors.

The results from this experiment were compared with two past studies. First, Cham and Redfern (2002) examined the effect of surface friction on gait within a research laboratory. They compared self-selected walking across smooth and rough surfaces, and observed a foot angle at heel contact that was 0.6 deg more plantar flexed, and foot angular velocity at heel contact that was 1.6 deg/s lower, on the smooth surface. This is unlike the current study where foot angle at heel contact was 0.7-1.3 degrees more dorsiflexed on the smoother surface, and foot angular velocity at heel contact was not different between environments. Second, Schulz (2011) investigated how visible surface height irregularities affected minimum toe clearance. Their results indicated minimum toe clearance was 2 times higher when visible surface height irregularities were present. Whereas in this study, small surface-height irregularities existed outdoors in the form of expansion joints, but minimum toe clearance was found to be lower. Several reasons can explain these differences. First, the outdoors and laboratory environment in this study do not necessarily replicate what was done previously. Differences in frictional properties of the flooring from the Cham and Redfern (2002) study and differences in surface height irregularities from the Schulz (2011) study could have led to differing responses in gait kinematics. Second, it is possible that factors conflicted with one another and prompted unexpected gait changes. Third, it is possible that other factors provoked changes in gait kinematics. For instance, visual orientation was not controlled for outdoors, which may have allowed for more precise control of foot movement with respect to the environment. Because participants were unaware of the data collection outdoors, gait changes may have occurred as a result of the Hawthorne effect, or participant awareness of measurements being collected. Past studies in clinical research have observed improvements in response variables as a result of participant awareness, such as enhanced cognitive function after more extensive follow-up in dementia patients (McCarney et al., 2007) and better well-being and reduced pain post-operation in patients aware of the study (De Amici et al., 2000). Behavioral improvements are difficult to predict in gait biomechanics research, and depend exclusively on participant interpretation. One hypothesis is that participants may shift to a more cautious gait by decreasing walking speed and increasing minimum toe clearance inside the laboratory. A second hypothesis is that participants may exaggerate kinematics by increasing stride length, increasing dorsiflexion at heel contact, and increasing minimum toe clearance inside the laboratory. A third hypothesis is that participants may decrease gait kinematics variability inside the laboratory.

In conclusion, gait inside a laboratory when participants were aware of being tested exhibited differences from gait outdoors in a natural setting when participants were unaware of being tested. It is unclear if these differences impair the ability to generalize gait study results to outside the laboratory. Nevertheless, this study brings to light differences in gait between environments that researchers should recognize.

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