Impact of Surface Stiffness on Lower Limb Stiffness and Symmetry During Gait

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Abstract

Human locomotion is a topic that has been studied for many years in biomechanics. To perform athletic tasks or everyday tasks, balance and symmetry is needed. Symmetry is the perfect balance and correspondence of the body or parts of the body. This concept has often been used to evaluate the normality of movements. Limb symmetry, specifically, is the equal actions of the lower limbs during movement. This is needed to perform tasks safely and efficiently without injury. Gait and movement symmetry has been used to predict lower limb injury risk for many populations and improve performance for athletes. It has also been used in assessment for rehabilitation processes and return to sport processes following injury or surgery. For many years, healthy gait was considered to be symmetrical for simplification purposes. However, many studies have contradicted that conclusion showing that even for has asymmetrical patterns. Deficits in symmetry can reduce quality of life for some individuals and can have detrimental health effects. Many measures have been used to assess symmetry in various tasks that have important implications on gait patterns. Another component of gait and movement that affects performance and injury risk is limb stiffness. Limb stiffness is the body's resistance to deformation when moments and forces are applied to it. The body has been shown to be modeled as a spring mass system that can restore and reuse energy. This is associated with the stretch shortening cycle during cyclic movements, such as running and walking. Limb stiffness is also associated with musculoskeletal loading that impacts performance and injury. Therefore, optimizing limb stiffness is important to improve utilization of elastic energy for athletic performance and reduce injuries associated with high and low limb stiffness values. Imbalances in limb stiffness have been shown to increase injury risk during walking and other tasks. Studying these imbalances using symmetry indices could give insight into the injury risk associated with this metric. In addition, limb stiffness in humans has been shown to change with the type of contact surface. This is associated with compensation methods used by humans when contacting different surfaces. Studying the relationship between limb stiffness symmetry and different surfaces during walking is important to observe how humans adjust and how it impacts injury risk. The purpose of this research was to assess the impact that surface stiffness has on limb stiffness symmetry during walking in healthy adults. To assess limb stiffness differences when transitioning to different surface stiffnesses anteriorly and posteriorly, the Normalized Symmetry Index (NSI) was determined for the two transition conditions and the control. The results showed that limb stiffness NSI was significant between the conditions (p=0.012). More specifically, a difference was seen between the stiff to compliant transition and the control (p=0.020) and the compliant to stiff transition and the control (p=0.032). These results show that humans do compensate when transitioning onto different surfaces. This is essential for understanding how humans adjust during real world walking and what patterns are used to maintain stability. To assess limb stiffness symmetry, when surface stiffness is different between limbs, the limb stiffness NSI was compared between two conditions. This included the side-to-side stiffness difference condition and the control condition. The results revealed that surface stiffness was not significant between conditions (p=0.244). Based on these results, limb stiffness symmetry is not significantly impacted when the surface stiffness is different between limbs. This contradicts prior studies that observed changes limb stiffness and symmetry depending on the surface stiffness. This may be due to overcompensation or the ability of the healthy adult population to quickly adjust to the surface stiffness changes before the measurements were taken. Simulating uneven surfaces is important to understand how humans compensate to maintain stability on surfaces in real world walking and for imbalances due to disorders. Further research is needed to study the changes in limb stiffness symmetry on different surfaces during walking to improve injury prevention methods.

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General Abstract

Humans perform many daily tasks and athletic tasks that have been observed in human movement analysis. To perform these tasks safely and efficiently, many factors must be considered. One of the important factors in performing tasks is symmetry. Symmetry is the perfect balance between parts of the body, such as the lower limbs during walking or gait. Gait in healthy adults was considered to be symmetrical for simplification purposes. However, studies have revealed that gait asymmetry is present in the healthy adult population during walking and other movements. Gait symmetry has been used to assess normality of gait patterns in healthy individuals and in clinical populations. Asymmetrical gait patterns can lead to injury and have detrimental effects on health. Therefore, limb symmetry has been an important metric to assess lower limb injury risk and improving injury prevention methods to correct asymmetrical patterns in healthy adults and other populations.

Another aspect of human movement that impacts injury is limb stiffness. Limb stiffness is the body's resistance to deformation under applied forces. High limb stiffness values have been associated with bony injuries due to increased loading. However, low stiffness values have been associated with soft tissue injuries. Therefore, regulating limb stiffness is important to reduce injuries in the long term. The type of contact surface during walking and other tasks has been shown to change limb stiffness values. Humans often encounter changes to surfaces when walking. For example, hikers who encounter uneven terrain or everyday walking on uneven pavement. Uneven surfaces have been shown to require more energy and work to move forwards during walking. Therefore, simulating uneven surfaces in the real world is important to understand how humans compensate on different surfaces. This could be important for understanding how limb stiffness imbalances on different surfaces affect injury. To quantify these imbalances, the metric of limb stiffness symmetry will be used. Limb stiffness imbalances due to surface stiffness are essential to assess how humans adapt to instability during real world walking. Therefore, this study aims to determine how humans adjust when transitioning to different surface stiffnesses and when surface stiffness is different between limbs.

To determine how humans adjust when transitioning to different surfaces of different stiffnesses, the limb stiffness symmetry was calculated using the Normalized Symmetry Index (NSI). This was calculated for three different surface stiffness conditions, consisting of a stiff to compliant transition, a compliant to stiff transition, and the control condition. The results showed that there was a significant difference between the NSI values of the three conditions. However, there was no difference between the two transition conditions. This indicated that there was no difference between the transition order. Based on the results, limb stiffness symmetry does change when transitioning to different surface stiffness conditions. This agrees with previous literature that suggests that surface stiffness has an impact on limb stiffness. This information is beneficial to understand the patterns humans use to compensate to maintain stability.

To determine how limb stiffness symmetry is impacted when surface stiffness is different between limbs, the limb stiffness NSI was calculated for two surface conditions. This included the side-to-side condition and the control condition. The results showed that there was no statistical difference between the limb stiffness NSI values of the two conditions. This shows that limb stiffness symmetry doesn't change when the surface stiffness is different between limbs, which disagrees with previous literature.

Overall, this information is important to understand how humans compensate when transitioning on different surfaces or walking on uneven surfaces. This is important to understand how stability is maintained despite imbalances for improvement of injury prevention methods.

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Table of Contents

List of Abbreviations

ANOVA	Analysis of Variance
COP	Center of Pressure
GRF	Ground Reaction Force
HJC	Hip Joint Center
NSI	Normalized Symmetry Index

List of Figures

List of Tables

Ch. 1 Introduction

Background

The term symmetry is described as the perfect correspondence between systems or parts of a system[1]. Symmetry in the movements of the human body is needed to perform tasks safely and effectively in daily life, in the workplace, and during sports participation. The degree of symmetry is often used to assess normality of different movements, such as gait, sports tasks, and other functions[2,3]. Symmetry has been used to study human movement for many years and provides a standard for normal gait patterns when assessing musculoskeletal diseases and other movement disorders[4-6]. This measure has also been significant in understanding recovery during rehabilitation following athletic injury, total knee arthroplasty, osteoarthritis, stroke survivors, and other clinical populations[1,7-9]. These asymmetries are often assumed to be due to compensatory patterns to avoid pain or heavily loading the surgical limb. Several studies have investigated asymmetries in kinematic, kinetic, and muscular activation patterns[10-13]. A prospective study that assessed load symmetry during gait on patients with unilateral cox arthrosis that had hip arthroplasty[14]. These researchers reported that patients that had hip arthroplasty experience higher peak loads compared to the controls. Another study found that limb asymmetries in knee loading during gait persisted after anterior cruciate ligament reconstruction[15]. Asymmetrical gait patterns have been known to be an indicator for return-to- sport decision making and overall lower limb injury risk. Symmetry values have been used to determine limb differences in strength and other measures for return to sport following anterior cruciate ligament (ACL) reconstruction surgery[16]. Additionally, people that have unilateral conditions such as osteoarthritis tend to have gait asymmetry which has a profound effect on their contralateral side over time[17]. These patients often load their non-surgical side more even when their surgical side is pain-free causing persistent asymmetry. This shows that there is an outstanding number of health risks associated with gait asymmetry that warrants more research[18].

For many years it was assumed for simplification purposes that the lower limbs were symmetrical during "healthy" gait[19,20]. However, it is now well known that gait asymmetries are prevalent in healthy adult populations [12,21]. There are many factors that influence movement symmetry in healthy populations, such as limb dominance, strength imbalances, and leg length discrepancies. Lathrop-Lambach et al. examined lower extremity joint moment asymmetry in 182 healthy adults during walking[21]. It was concluded that more than half of the adults surpassed 10% asymmetry in the kinematic and kinetic variables of interest. This study along with other previous studies demonstrate that gait asymmetries in healthy populations exist and requires further research. This caused researchers to consider asymmetry in all analyses of lower limb movements in addition to gait [11]. This is important to understanding the expected baseline of symmetry when comparing healthy adult populations to clinical populations.

There is still no single accepted standard for assessing symmetry, which makes it a challenge to compare studies and criteria for clinical decisions. Assessing symmetry has two main components which are the gait parameters of interest and the method used to calculate symmetry. A variety of metrics have been proposed in the literature for assessing symmetry. Although there are several indices proposed in research, they all have advantages and disadvantages when assessing different variables. The Ratio Index (SI) was first introduced in 1974 by Ganguli et al[22]. This study evaluated gait differences in unilateral below-knee amputees walking with prostheses. This index used the ratio of the values for both limbs as the symmetry index and expressed the result as a percentage as shown in Equation 1.

$$RI = \left(1 - \frac{X_R}{X_L}\right) * 100 \qquad (1)$$

An RI equal to 0 % indicates perfect symmetry, while a RI greater than 100% indicates asymmetry. Percentages can exceed 100% and are not bounded. This index has been shown to be overly conservative pertaining to small values in the denominator[23]. Therefore, there was a need to quantity symmetry using a different method. The Symmetry Index (SI) was later proposed by Robinson et al. in 1987[24]. Temporal and kinetic variables of gait were assessed for changes in symmetry before and after treatment sessions. This is a more general modification to the RI and became the most used index. The denominator represents the average of the absolute value of both limbs shown in Equation 2.

$$SI = \left(\frac{2*(X_n - X_i)}{|X_n| + |X_i|}\right) * 100 \qquad (2)$$

The X_n and X_i represent the non-injured and injured limbs respectively. Again, an SI value of 0% indicates perfect symmetry and an SI value greater than 100% indicates full asymmetry. Like the RI, the SI can exceed 100% and is not bounded. For this reason, the absolute value is reported in some applications. A modification to the SI by a Herzog et al. in 1989 allowed for the identification of limb dominance trends[25]. During this study, ground reaction forces during gait were obtained using values from the right and left leg instead of the injured and non-injured legs. However, positive and negative symmetry values can change the average symmetry value for an individual. To address this disadvantage, the Absolute Symmetry Index (ASI) was created in 2003 by Karmandis et al.[26] shown in Equation 3.

$$ASI = \left(\frac{2*|X_R - X_L|}{X_R + X_L}\right) * 100 \qquad (3)$$

This index takes the absolute value of the variable for the right leg minus the value of the variable for the left leg. When the value of the ASI is zero this indicates perfect symmetry and values can exceed 100%. Several other common measures and modifications have been proposed such as the Gait Symmetry Index (GA)[27], the Symmetry Angle (SA)[28] and the Normalized Symmetry Index (NSI)[23]. A study conducted by Plotnik et al in 2005 investigated motor performance asymmetry in patients with Parkinson's disease[27]. The GA was proposed in this research which applies a logarithmic transformation to the ratio index to get a symmetry percentage displayed in Equation 4.

$$GA = \ln\left(\frac{X_L}{X_R}\right) * 100 \tag{4}$$

The X_L and X_R values represent the left and right leg respectively. In this equation, a negative number is obtained when the value of the limb in the denominator is greater than the value in the numerator. A limitation of the GA is that it can only be calculated when the X_L to X_R ratio is positive, which is not practical when the variable of interest can be positive or negative. Then in 2008, Zifchock et al suggested the SA in a study that was examining limitations of the symmetry index to define a new method of evaluating symmetry[28] shown in Equation 5.

$$SA = \left(\frac{45^\circ - \arctan\left(\frac{X_L}{X_R}\right)}{90^\circ}\right) * 100 \tag{5}$$

The SA uses angular measurements during movements obtained by a motion capture system to define the level of symmetry. This is a disadvantage because it mainly does well with angular symmetry, instead of a variety of other measures. Similar to the other indices, a value of 0 indicates perfect symmetry, while a value less than 100% indicates some level of asymmetry. Finally, the NSI is the most recently developed modification of the SI[23]. Unlike the other indices, the NSI also normalizes across several trials with a minimum of three. This is a bounded index where the NSI value is either equal to 100% or -100% indicating maximum asymmetry. A positive value indicates the non-surgical or dominant limb metric was larger and a value of 0 indicates perfect symmetry. X_{NS} and X_S indicate the non-surgical/dominant and the surgical/non-dominant limb measures shown in Equation 6.

$$NSI = \left(\frac{X_{NS/D,t} - X_{S/ND,t}}{max_{t=1:n}\left(\max\left(0, X_{NS/D,t}, X_{S/ND,t}\right)\right) - \left(\min\left(0, X_{NS/D,t}, X_{S/ND,t}\right)\right)}\right) * 100 \tag{6}$$

This numerator represents the values for a single trial, while the denominator represents the values across n number of trials. The NSI has been shown to be reliable and performs well with low levels of symmetry making it easy to use in any setting[23]. Each of these indices have been used to assess a number of biomechanical measures. The variables that are being assessed influence what index would be most appropriate. The primary variable of interest in this study is limb stiffness and the NSI will be used to assess limb stiffness symmetry.

Lower limb stiffness and symmetry are two very important components of gait. Knowledge of lower limb stiffness and symmetry is required in many applications that involve emulating human walking, including prosthetic limbs, bipedal walkers, and lower limb exoskeletons[29-32]. Stiffness is generally defined as the resistance of an object or body to deformation under an applied force[33]. It has been shown that very high or low levels of leg stiffness can be an influential factor in functional performance during movements or lead to injury [34]. Prior studies have shown that a stiffer leg facilitates the efficient store and reuse cycle enhancing running performance [35]. Additionally, some evidence has shown that increased stiffness can increase the risk of bone damage and decreased stiffness could be associated with soft tissue injuries[34,36,37]. Additionally, it has been suggested that limb stiffness is essential for optimal utilization of the stretch shortening cycle during movements[33]. Previous studies have also explored the relationship between stiffness and performance during running, hopping, jumping, and other tasks[35,38-42]. Amarpatzis et al. conducted a study on the effect of leg stiffness on mechanical power and take-off velocity during drop jumps[41]. It was reported that mechanical power could be maximized by reaching an optimum stiffness value which is important because many sports require mechanical power output to perform well. Therefore, investigating the effects of mechanical limb stiffness on these tasks is important for enhancing physical performance and assessing injury risk. Exploring this could give insight into the improvement of training interventions to enhance lower limb stiffness, such as eccentric strength training and plyometrics[35]. Most of this research on limb stiffness pertains to performance and injury regarding athletes and sports tasks. However, there hasn't been as much research on the effects of limb stiffness on injury during walking.

The term stiffness originated as a part of Hooke's Law[33,43]. This law is defined as $F = kx$, where F indicates the force to deform the object, and k is the spring constant, and x is the distance that the object was stretched or compressed. From this law it was concluded that the change in length of the object is directly proportional to the force acting upon it. Applying this principle to the human body is challenging because stiffness can be defined at different levels. A simple spring mass system has been used to describe the biomechanics of a variety of body movements involving the stretch shortening cycle[33,44]. During the stretch-shortening cycle movements, joint stiffness and joint angles usually determine limb stiffness [40,45]. It can also be attributed to the magnitude of activation from agonist muscles as well as the coactivation of antagonist muscles before and immediately after initial contact[45-47]. Lower limb stiffness depends on the stiffness of all compliant tissues in the body including the tendons, ligaments, blood vessels, or bones[33]. During cyclic movements the musculoskeletal structure of the lower limbs alternately store and reuse elastic energy, therefore, they can be described as a spring. From this model, two forms of lower limb stiffness calculations can be formed[33,44,48]vertical stiffness k_{vert} shown in Equation 7 and leg stiffness k_{leg} shown in Equation 8.

$$k_{vert} = F_{max} \cdot \Delta {y_c}^{-1} \tag{7}$$

$$k_{leg} = F_{max} \cdot \Delta L^{-1} \tag{8}$$

Vertical Stiffness is primarily used during linear vertical movements such as jumping and hopping. Leg stiffness is typically used during horizontal and vertical movements such as jumping and running as well [33]. Stiffness is the result of force and length, thus, both calculations are ratios of the peak vertical ground reaction force (GRF) to the peak center of mass (COM) displacement for vertical stiffness and peak leg compression for leg stiffness. When the COM is moving purely in the vertical direction, the vertical stiffness and the leg stiffness are identical. Leg stiffness can be defined using various methods including a one-dimensional, two-dimensional, and three-dimensional method[49]. Depending on the task being performed, a certain method may be more appropriate than others. A three-dimensional approach is most appropriate for running and walking because leg movements during gait typically occur in three dimensions, therefore, a multiplanar method accounts more for all the force and length components in the stiffness equation[44,49,50]. This method is essentially the k_{leg} calculation from Equation 8, however, this equation uses the peak resultant GRF and the three-dimensional change in limb length (ΔL_{3D}) instead of the max ground reaction force and the peak leg compression. The change in limb length is defined as the limb length at initial contact to the peak vertical GRF. The limb length is calculated using the three-dimensional positional coordinates of the hip joint center (HJC) and the center of pressure (COP) shown in Equation 9.

$$L_{3D} = \sqrt{(HJC_z - COP_z)^2 + \left(HJC_y - COP_y\right)^2 + (HJC_x - COP_x)^2} \tag{9}$$

Most of the studies exploring limb stiffness and locomotion have been conducted on smooth even laboratory floors[51,52]. However, in the natural world humans often encounter walking and running on uneven surfaces[53]. Therefore, there is a need to explore the role that surface stiffness plays in leg stiffness symmetry and how humans adjust to changes in surfaces. Several studies have investigated the influence of surface stiffness on leg stiffness during single dynamic events such as hopping, landing, and jumping[54-57] . It has been suggested that leg stiffness is increased when landing on compliant surfaces reducing the energy absorption by the musculoskeletal system during landing and running[54-56]. Other studies have explored the effect of surface stiffness on gait control mechanisms, inter-leg coordination, and muscle activation during human locomotion[58-61]. MacLellan & Patla et al found that the tibialis anterior and soleus muscles were activated more on a compliant surface compared to a more rigid surface[60]. In addition, another study was investigating sensorimotor mechanisms during gait by introducing perturbations of different surface stiffnesses during different phases of the gait cycle[62]. These researchers observed that the soleus muscle activity decreased on the contralateral leg when a unilateral perturbation of a different surface stiffness was presented during the stance phase. While the impact of surface stiffness on leg stiffness and other mechanisms has been studied during walking and athletic tasks, little is known about the effects of surface stiffness on limb stiffness symmetry specifically during walking in healthy adults. This could have significant implications on how humans compensate for imbalance and instability. Simulating imbalances on uneven surface and transitioning to different surfaces gives further insight on instability and compensatory gait patterns during walking.

Motivation, Purpose, and Aims

Assessing symmetry during walking can improve our understanding of the complicated dynamic human system and the interplay between limbs[63]. Symmetry is an equal balance between systems or parts of a system. Movement symmetry is typically assessed during specific tasks such as gait, running, and sport specific tasks[64,65]. Symmetrical movements of the human body are essential for performing safe and efficient movements during activities of daily life, thus decreased movement symmetry has been identified as an injury risk factor[66]. Symmetry of various measures have been studied to evaluate differences between limbs during human locomotion[11,12,67,68]. Studying kinematic and kinetic asymmetry during gait and other movements is essential to identify functional deficits and assess lower limb injury risk.

Additionally, another aspect of human movement that can influence injury risk is lower limb stiffness. Limb stiffness is a term that describes the body's resistance to deformation when forces and moments are applied to it[33]. The leg can be described as a spring-mass model that stores and reuses elastic energy during cyclic movements, such as running and walking [39]. Limb stiffness imbalances have been shown to negatively impact performance and injury [34]. Too much leg stiffness has been associated with injuries to the bone and increased load on the musculoskeletal system[34]. Leg stiffness values have been shown to change based on contact surface[45,52,56]. This is an important factor to consider when observing how humans compensate for changes in surfaces.

Previous studies have examined the impact of surface stiffness on joint mechanics and leg stiffness using flooring or shoes as a factor[52,69,70]. Other studies have explored the impact of compliant surfaces on sensorimotor mechanisms in human movement during certain tasks[58,71]. Although these studies have been insightful, most of them examined impacts of surface stiffness in the context of sports tasks and muscle activation during walking. The examination of the impact of surface stiffness and its variation on movement symmetry in a healthy adult population outside the context of sports is relevant to daily life but is yet to be explained. Understanding how the human system responds to changes in surface stiffness to maintain stability will allow for improved understanding of the control strategies and how humans handle changes in substrate. This will also help understanding of the potential injury risk associated with overloading to compensate for this change. Therefore, the purpose of this research is to assess the impact that surface stiffness has on limb symmetry in joint mechanics and leg stiffness during walking in healthy adults. This would give clinicians and researchers useful information about the way humans compensate for changes in surface stiffness during gait and what effect that has on lower limb injury risk. These questions will be investigated through the following aims.

Specific Aim 1: **Examine the impact of differing surface stiffness anteriorly and posteriorly on limb stiffness symmetry during gait**

Hypothesis: Limb stiffness will be less symmetrical when surface stiffness varies anteriorly to posteriorly compared to the control condition.

Specific Aim 2: **Examine the impact of differing side to side surface stiffness on limb stiffness symmetry during gait**

Hypothesis: Limb stiffness will be less symmetrical when surface stiffness varies between left and right limbs compared to the control condition.

The completion of these aims will advance gait training and rehabilitation methods for athletes and clinical populations. This research will also provide insight into how humans adjust and maneuver on surfaces when walking with varying stiffnesses, providing a basis for further research on this topic.

Ch 2. Examine the impact of differing surface stiffness anteriorly and posteriorly on limb stiffness symmetry during gait

Abstract

Introduction: Limb stiffness describes the resistance of the human body to deformation under applied forces[33]. Butler et al reported that high and low levels of symmetry can be associated with bone injuries or soft tissue injuries, respectively[34]. Therefore, regulating limb stiffness is essential to reducing injury. A factor that has been shown to affect limb stiffness is the type of contact surface [45,56]. Simulating different types of surfaces is important to emulate human walking in real world conditions where humans encounter different surfaces. Therefore, incorporating surface stiffness into studies is beneficial to understanding how humans compensate when transitioning to a different surface. Although the impact of surface stiffness on limb stiffness and other symmetry measures has been studied in athletes, there is still a gap in knowledge regarding how limb stiffness symmetry changes when transitioning to different surfaces when walking in healthy adults. It was hypothesized that limb stiffness will be less symmetrical when surface stiffness is different anteriorly and posteriorly compared to the control.

Methods: Limb stiffness symmetry was quantified using Normalized Symmetry Index (NSI). NSI is a bounded index where ±100 is the maximum level of asymmetry and 0 is perfect symmetry[23]. Participants completed eight, 10-meter walking trials on three different surface stiffness conditions, consisting of the stiff to compliant transition (STC), compliant to stiff transition (CTS), and the control condition. The NSI was calculated using a minimum of three trials. Statistical analysis was conducted in JMP (SAS Institute Inc., Cary, NC) with an alpha level of 0.05. A linear mixed effects model with average walking speed as a covariate was used to determine differences in limb stiffness NSI values between the conditions. A Tukey's Honest Significant Test was used for post-hoc testing.

Results: The limb stiffness NSI values were different between conditions(p=0.012). Specifically, the STC condition (p=0.020) and the CTS (p=0.033) condition were significantly greater, decreased symmetry, compared to the control. However, the STC and CTS condition did not differ (p=0.976) signifying that the transition order does not affect limb stiffness symmetry.

Discussion: These results show that limb stiffness symmetry was impacted when between surfaces. This supports the hypothesis and agrees with previous literature that limb stiffness and symmetry changes on different surfaces[52,56]. Understanding what compensation patterns are used to combat imbalances due to surface stiffness or disorders is important for injury prevention. Future work could incorporate other measures, such as joint work, ground reaction force, and joint excursions to better understand the gait changes that occur as individuals modulate limb stiffness.

Introduction

Limb stiffness is a metric that has been used to assess human and animal locomotion for many years[33,44]. This concept of stiffness is based on Hooke's Law stating that the force required to deform an object or body is proportional to the (spring) constant and the distance it is stretched or compressed[72]. Therefore, limb stiffness is used to determine the human body's resistance to deformation when subject to ground reaction forces or moments that are applied to it. The summative musculoskeletal stiffness including the muscles, tendons, ligaments, cartilage, and bone all contribute to lower limb stiffness[34]. Therefore, stiffness is a measure of musculoskeletal function. There are two main forms of lower limb stiffness including vertical and leg stiffness[33]. Leg stiffness is primarily used in instances when the lower limb contacts the ground in a non-vertical position. Therefore, leg stiffness is the more appropriate measure to use for evaluating lower limb stiffness during walking due to the dynamic multiplanar characteristics during this task[49,50,73]. This measure has been shown to be a key aspect in understanding human movement and lower limb behavior.

Most of the research pertaining to stiffness is in the field of sports science, performance, and injury. It has been described that mechanical stiffness influences athletic movement and variables such as rate of force generation, storage of elastic energy, and sprint mechanics[34,38]. Leg stiffness has been assessed during running, long jumping, landing, and other vertical movements[41,44,45]. These studies have shown that leg stiffness has a significant influence on functional performance demonstrating that both low and high limb stiffness values have a significant effect on injury and performance. Leg stiffness has proven to play an important role in performance and injury during running, hopping, and landing[35,39,74] Someone who can successfully optimize their leg stiffness can improve performance by efficiently storing more elastic energy. High values of leg stiffness have been associated with injury due to the increased work and load on the musculoskeletal components[34,75]. Specific to gait, stiffness is an essential factor in optimizing human locomotion by efficiently utilizing the storage of elastic energy in the musculoskeletal system[34]. Akl et al. concluded that leg stiffness is decreased at different walking speeds[73]. This highlights the importance of energy recovery and optimizing leg stiffness to avoid overloading joints which could have negative long-term effects.

It is further suggested that leg stiffness during gait can vary with different footwear and surface conditions[67,76]. However, more research is needed to understand how this affects injury and how individuals adjust to surface changes. This relationship is important to investigate because humans are often exposed to different surfaces in the natural world and must transition when walking, running, or other athletic tasks. A 5-year study conducted by Meyers and Barnhill investigated the differences between natural grass and field turf and how it affects sports injury risk[77]. It was concluded that certain injury mechanisms could be possibly correlated to the type of playing surface. It also has been reported that leg stiffness increases on more compliant surfaces during landing, hopping, and running to accommodate for this change in surface stiffness[54-56]. In addition, another study evaluating how surfaces with different levels of compliance change ankle moment and stiffness regulation found that surface stiffness did affect the regulation of ankle moment and stiffness depending on the phase of gait[78]. They also found that depending on the level of compliancy, certain muscles could be activated more to respond to the type of surface. Even though there are studies that have explored these factors in real world conditions, many of them have been conducted within an athlete population and using different measures. Thus, further research is needed to simulate the effects of different surface stiffnesses during walking in non-athletes. Identifying how healthy adults adjust limb stiffness when surface stiffness changes during walking is crucial. This research could help observe how humans respond and compensate when transitioning to and from different surfaces.

Symmetry is another important aspect of human movement that has significant influence on performance and injury. This is a significant factor when measuring how leg stiffness during gait varies between limbs when transitioning to a different contact surface. The term symmetry in reference to the human body is described as perfect proportion and balance between two systems or parts of a system[1]. Lower limb symmetry is important to perform daily or athletic tasks safely and efficiently. Lower limb symmetry has been a metric used to assess lower limb injury risk, readiness to return to sport decision making, and functional performance[79,80]. Many studies have examined various measures to examine differences between limbs and how they affect performance. As previously mentioned, limb stiffness is one of the many measures that have been shown to affect injury and performance in human movement. Imbalances in limb stiffness can cause detrimental performance, increase soft tissue injuries, increase musculoskeletal loading[75,81]. Therefore, it is important to explore the relationship between injury and symmetry, specifically leg stiffness symmetry, more in depth.

Exploring the effect of transitioning to surfaces of different stiffnesses on leg stiffness symmetry more is important to understand the adjustment that humans make. While leg stiffness, symmetry, and surface stiffness have been shown to shown to contribute to injury and performance during different movements, there is a gap in knowledge regarding this relationship between these three factors during walking in healthy adult populations. Therefore, the purpose of this study is to examine the effects of transitioning to different surface stiffness on limb stiffness symmetry during walking in healthy adults. We hypothesize that limb stiffness symmetry will be greatly reduced compared to the control condition. Furthermore, limb stiffness symmetry on different surfaces is important to investigate because humans are often exposed to different surfaces in the natural world. This research could help observe how humans respond and compensate when transitioning to different surfaces.

Methods

Sixteen healthy adults were recruited from the Virginia Tech community to participate in this study. The term healthy was defined as being physically active, pain free, symptom free, and uninjured a the time of testing. In addition to eligible participants were required to be between the ages of 18 and 40, have a shoe size between 6.5 - 11 for males and 7- 11 for females due to available shoes, and be able to walk unassisted for 30 minutes. Participants were excluded from the study if had a self-reported current or recent lower-extremity injury within the last 2 months that limited their physical activity for more than two days, had a prior serious lower extremity injury or surgery, or if they had chronic back pain. This study was conducted under an approved institutional review board protocol. All participants signed informed consent prior to data collection. In addition, participant demographics including age, height, and weight were all recorded prior to data collection.

A 10-camera motion capture system (Qualisys, Gothenburg, Sweden) recorded at 240 Hz and eight time-synced force plates (AMTI, Watertown, Massachusetts) recorded at 240 Hz were used to capture all kinematic and kinetic data. Participants were provided with tight fitting athletic clothing and standardized, laboratory-issued neutral cushioned running shoes (Nike Zoom Pegasus; Nike Inc., Beaverton, OR, USA). A modified Helen Hayed marker set was used for marker placement[82]. Participants had 43 retroreflective markers, consisting of 27 individual markers, a cluster of four markers for each thigh and each shank. The individual markers included the sacral, anterior superior iliac spine, posterior superior iliac spine, the medial and lateral malleolus and femoral epicondyle, greater trochanter, inferior heel, superior heel, lateral heel, 1st metatarsal, and 5th metatarsal. Individual markers were placed bilaterally on the lower extremity portion of the body shown in Figure 1. After marker placement, a static trial was collected for five seconds which was used to calculate joint centers and anatomical axes during walking trials when the data is processed and analyzed. Following the static trial, the medial femoral epicondyle, medial malleolus, 1st metatarsal, and 5th metatarsal markers were removed from each limb.

Figure 1: Marker Placement: a) Female Anterior View, b) Female Posterior View

Two different foam surfaces were used to impose a “stiff” and “compliant” surface. The stiff foam was made of nylon, while the compliant foam was made of polyurethane. The density of the stiff foam is 3 lbs/ft^3 and the density of the compliant foam is 2 lbs/ft^3. The pressure to compress the stiff and compliant foam 25% is 28 psi and 1 psi, respectively. The dimensions of the foam pieces were 60x30 cm panels and secured to embedded force plates. Additional panels were placed before and after the embedded force plates to reduce the effects of the slight elevation change from the lab floor. All participants were instructed to walk 10 meters at a self-selected pace for 8 trials along one of two surface stiffness conditions (control, anterior to posterior stiffness difference) shown in Figure 2. The control condition consisted of all stiff foam to create a baseline form comparison. The anterior-to-posterior condition consisted of stiff foam leading up to and across the first four force platforms and the compliant foam on the next four force platforms (Figure 2).

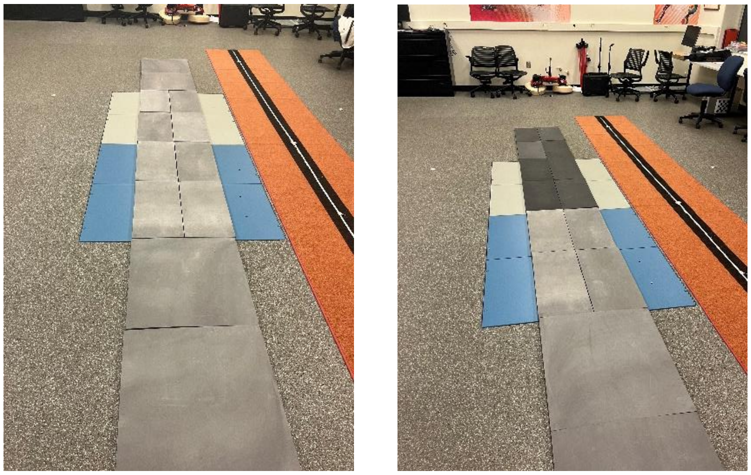

Figure 2: Two different surface stiffness conditions: Left to Right: control, anterior-to-posterior

The order of the conditions was picked at random prior to the walking trials. The anterior-to-posterior condition was separated into two sub-conditions. This consisted of the transition from stiff to compliant surface and from compliant to stiff surface. Therefore, the eight trials were split amongst the front to back condition, creating four stiff to compliant (STC) transitions and four compliant to stiff (CTS) transitions. A trial was considered successful if one foot hit each force plate across the walkway. Participants were also instructed to keep their eyes up as they were walking. In order to ensure that each foot hit each force plate, participants were asked to complete a couple of practice trials to adjust their starting position if needed. To prevent fatigue, participants were given a 20 second rest in between trials.

Three-dimensional data was processed in Qualisys Track Manager (Qualisys, Gothenburg, Sweden) to obtain trajectories of all markers during the movement. Visual 3D (C-Motion, Inc, Germantown, MD) was used to filter marker data and force plate data using a low pass Butterworth filter with a cut off frequency of 7 Hz and 100 Hz, respectively. All metrics that included force were normalized to body weight. Additionally, Visual 3D was used to analyze the data and export the center of pressure (COP), hip joint center (HJC) location, and ground reaction forces (GRF). A custom MATLAB (MathWorks, Natick, MA) code was created to calculate leg length (L_{3D}), leg stiffness (k_{leg}), and leg stiffness NSI during the weight acceptance phase of the middle two consecutive using the following three-dimensional leg stiffness equation[50]:

$$L_{3D} = \sqrt{(HJC_z - COP_z)^2 + \left(HJC_y - COP_y\right)^2 + (HJC_x - COP_x)^2}$$

$$k_{leg} = \frac{ResultantGRF_{max}}{\Delta L_{3D}}$$

Limb stiffness NSI was determined using a minimum of three trials[23]:

$$NSI = \left(\frac{X_{Compliant,t} - X_{Stiff,t}}{max_{t=1:n}\left(\max\left(0, X_{Compliant,t}, X_{Stiff,t}\right)\right) - min_{t=1:n}\left(\min\left(0, X_{Compliant,t}, X_{Stiff,t}\right)\right)}\right) * 100$$

The limb on the compliant foam was used as the dominant limb within the NSI calculation because it was assumed limb stiffness would be greater on the compliant foam. For the control condition, the right leg was considered the dominant leg in the NSI calculation. An NSI value of 0 indicates perfect symmetry, while a positive NSI value indicates the compliant foam side exhibited greater leg stiffness values. Statistical analysis was completed in JMP (SAS Institute Inc., Cary, NC) using an $\alpha = 0.05$. An analysis of variance (ANOVA) test was conducted to identify any differences in average walking speed between the conditions. A linear mixed effects model was used to examine the effects of surface condition (control, STC, CTS) on limb stiffness symmetry. A Tukey's honest significance test was used to explore the pairwise comparison of mean limb stiffness NSI values between the conditions.

Results

Sixteen adults consisting of fourteen females and four males between the ages of 18 and 40 completed this study. The mean age of the participants was 23yrs ±4yrs. The mean height and weight of participants was 1.67m ±0.09m and 70.3kg ±11.7kg, respectively. The average walking speed was not significantly different between surface conditions (*p*=0.972; Table 1). However, there was a significant difference (*p* =0.012; Table 1) between the limb stiffness NSI values of the different surface stiffness. Specifically, there was a significant difference between the stiff to compliant transition and the control (*p*=0.020) and between the compliant to stiff transition and the control (*p*=0.033) shown in Figure 3. However, the two anterior-to-posterior transitions did not differ between each other (*p*=0.976). This indicates that the order and transition from compliant to stiff and stiff to compliant was insignificant. In addition, the results show that limb stiffness symmetry is significantly reduced when transitioning to surfaces of different stiffnesses.

Table 1. Mean and standard deviations for Gait Speed and Limb Stiffness NSI by condition

	Control	STC	CTS	*p*-value
Gait Speed (m/s)	1.16m/s ±0.11m/s	1.15m/s ±0.11m/s	1.14m/s ±0.12m/s	0.972
Limb Stiffness NSI	12.4 ±4.2	27.7 ±4.2*	26.6 ±4.2*	0.012

*Significantly different from control

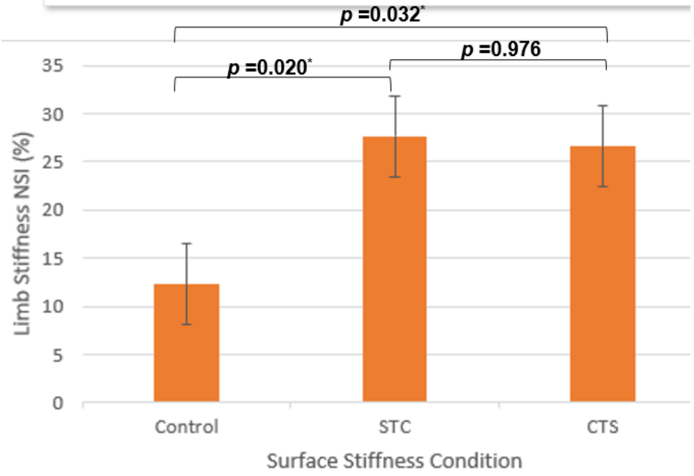

Figure 3: Mean limb stiffness NSI values for the control, stiff to compliant(STC), and compliant to stiff(CTS) surface stiffness conditions

Discussion

The goal of this study was to determine the impact that surface stiffness differences have on limb stiffness symmetry during walking in healthy adults. A better understanding of how limb stiffness changes when transitioning to and from different surface stiffness is important to understand how humans react to changes in surface. The hypothesis was that limb stiffness symmetry would be significantly reduced for the anterior-to-posterior and the leg stiffness would be greater for the more compliant surface. Limb stiffness NSI was shown to be significant between conditions (anterior-to-posterior stiff to compliant transition, anterior-to-posterior compliant to stiff transition, and control), specifically between both transitions and the control condition. This indicates that regardless of the transition order, limb stiffness symmetry is impacted compared to the control. Therefore, the hypothesis was supported by the results.

This agrees with previous work suggesting that limb stiffness does change depending on surface stiffness[45,67,78]. This is important to understand how humans compensate when transitioning to a different surface stiffness and what patterns are used to maintain stability. This is beneficial to understanding how leg stiffness increases the load and work being done by the musculoskeletal system in an attempt to increase stability on different surfaces[34]. Understanding this compensation pattern could improve injury prevention methods that could help correct limb stiffness imbalances. Additionally, more research on this topic could aid in corrective measures to decrease musculoskeletal load which could have harmful effects leading to increased risk of bone damage and injuries over time. Future studies could investigate other measures that humans use to adapt to changes in surface stiffness, such as joint angles, joint work, and joint moments. In addition, other types of surface transitions could be incorporated as well. Lastly, this study shows that healthy adults experience decreased symmetry when transitioning to different surfaces. Future research could also use this study as a basis for comparison to limb stiffness changes in clinical populations to assess their compensatory patterns.

A limitation of this study was the sample size. This study could have benefited from a larger sample size with more trials per condition. This may have shown more differences in limb stiffness NSI values between transitions. Another limitation was the number of steps taken before the measurements that were taken on the force plate. Having more steps before the stiffness changes could have impacted limb stiffness measurements. In addition, the standardized lab shoes which contain their own level of compliancy could have affected the limb stiffness values as well. To accurately assess how limb stiffness symmetry changes with surface stiffness, it may be beneficial to test participants while barefoot. Lastly, the results can only be concluded for these two specific types of surfaces.

This work was able to simulate different surface stiffnesses that could be encountered in the real-world during walking. It was shown that participants became less symmetrical when transitioning between surfaces of different stiffnesses. This is important to observe how humans modulate leg stiffness to combat imbalances during walking, which could be due to contact surface or medical conditions. This could be used as a baseline to compare healthy adults to clinical populations.

Ch 3. Examine the impact of differing side to side surface stiffness on limb stiffness symmetry during gait

Abstract

Introduction: Symmetry describes the perfect balance between the body or parts of the body[1]. Assessing gait asymmetry is important to understanding injury risk and to assess normality of gait patterns in healthy and clinical populations. It has been shown that even gait in healthy adults exhibits asymmetry during walking and other tasks, which can lead to injury[19,20]. Understanding these imbalances is important for injury risk assessment and injury prevention methods. Additionally, limb stiffness has been shown to be a contributing factor to injury risk and performance during walking and other movements[34]. Surface stiffness is a factor that has been shown to change limb stiffness which could lead to injury as well[56,77]. Humans often encounter different surfaces when uneven terrain is presented in real world walking. Imbalance and walking on uneven terrain require more energy and musculoskeletal load[53,75]. Therefore, exploring how humans compensate when surface stiffness is different between limbs is important for injury prevention and reducing energy costs. Even though there is research on how limb stiffness changes with surface stiffness, there is still a gap in knowledge regarding how limb stiffness symmetry changes when surface stiffness is different between limbs during walking in healthy adults. It was hypothesized that limb stiffness will be less symmetrical when surface stiffness is different between limbs.

Methods: The collection of kinematic and kinetic data was captured with AMTI force plates and a motion capture system. Limb stiffness symmetry was quantified using Normalized Symmetry Index (NSI), which is a bounded index. An NSI value of zero indicates perfect symmetry, while ±100 is maximum asymmetry[23]. Participants walked for 10 meters on two surface conditions (side-to-side and control) for eight trials. Statistical analysis was conducted in JMP (SAS Institute Inc., Cary, NC) with an alpha level of 0.05. To test the significance of the limb stiffness NSI values between conditions, a linear mixed effects model with average walking speed as a variable was used. A Tukey's Honest Significant Test was used for post-hoc testing.

Results: The Limb stiffness NSI values were insignificant between conditions(p=0.244). This shows that there was no difference in limb stiffness symmetry between the conditions.

Discussion: These results show that limb stiffness symmetry was not significant between conditions which did not support the hypothesis. This disagrees with previous literature stating that limb stiffness changes depending on surface stiffness[52,58]. Simulating uneven surfaces allows for the understanding of how humans compensate to maintain stability on uneven surfaces or when other limb imbalances are present. This is essential to improve injury prevention methods to correct imbalances.

Introduction

Symmetry in biomechanics is the balance between the actions of both sides of the body during movement[1]. For many years, symmetry has been evaluated to study human movement and assess normality of gait patterns[2]. Movement symmetry is needed to effectively perform certain tasks without injury, such as running and walking. Gait asymmetry is used to explain many pathologies and is an important clinical issue for people with knee and hip osteoarthritis, scoliosis, people who have had ACL reconstruction surgery, and other orthopedic conditions[4,6]. People with unilateral conditions or that have had unilateral joint arthroplasty, specifically develop compensatory mechanisms to avoid loading their surgical leg as much[83]. This causes persistent gait asymmetry putting the contralateral side at risk for developing the condition or sustaining injury. Therefore, symmetry is an important tool that can be used in the evaluation of lower limb injury risk. Symmetry has also been used in clinical decision making during the rehabilitation and return to sport process following athletic injury[79]. It has been proposed that symmetry of the lower limbs during functional tasks can be used to characterize successful rehabilitation[84]. Thus, asymmetry during certain tasks have been shown to be important factors in injury risk assessment and how humans adapt following injury or surgery. Haddad et al. investigated intra- and interlimb gait adaptations in response to increased asymmetry during walking[85]. This study concluded that spatio-temporal symmetry and interlimb coordination changes occurred when humans tried to adapt to the increased load that was applied to their non-dominant leg. Studies like this show that it is important to identify how humans develop compensatory mechanisms to adapt to imbalances and persistent gait asymmetry.

A factor that could simulate imbalance, thus, giving further insight on compensatory mechanisms and how humans respond is the type of contact surface. Surface stiffness is another factor that has been recently introduced in literature to observe how humans adjust during walking, running, hopping, and performing other athletic tasks on uneven surfaces[56,58,67,69]. Walking adaptability is how humans modify their gait pattern to complete tasks and deal with environmental demands[86]. This is a crucial component to safe locomotion within the home and outside environments. Injuries, surgeries, cerebral palsy, strokes, leg length discrepancies and other neurological and musculoskeletal disorders often affect mobility and walking adaptability. Sekiguchi et al conducted a literature review on how stroke patients adapt to the demands of walking on uneven terrain in real world environments[87]. Since it is difficult to walk following a stroke, increasing the ability to adapt during daily walking activity is important to increase physical activity. This is essential for rehabilitation programs and recovery. In addition, previous studies have explored the effect of floor stiffness on spatio-temporal parameters and kinematics during walking and sports tasks[51,62,69]. A study conducted by Skidmore et al. investigated how gait control mechanisms are affected when a perturbation of a different surface stiffness is presented while walking[62]. They found that there was an increase in tibialis anterior and soleus activation, as well as increased ankle, knee, and hip flexion. This study demonstrated that surface stiffness does influence inter-limb coordination mechanisms and how humans respond to differences in surface stiffness. Humans encounter many different types of surfaces when running, walking on trails, uneven pavement, and other uneven surfaces in everyday life[53]. This requires humans to adjust and respond to environmental demands. It has been shown that different energetic costs are associated with differences in terrain, such as grass, snow, concrete, etc [53,88,89]. Limb stiffness can be regulated to reduce the energy needed to stabilize and move forward when walking on uneven surfaces. This helps understand gait control strategies for imbalances and could give insight on how limb stiffness changes on natural terrain versus smooth ground or laboratory floors. However, the biomechanical factors contributing to this increase in energetic cost and mechanical work is unknown. One of the biomechanical factors that have been shown to change with surface stiffness is limb stiffness.

Limb stiffness originates from Hooke's Law and is used to measure how the lower limb resists deformation when forces and moments are applied to it[33]. During certain movements, the body's musculoskeletal system acts as a spring that stores and releases elastic energy. Limb stiffness and the spring mass model have been used to describe these cyclic motions. Many studies have reported lower limb stiffness as leg stiffness, vertical stiffness, or joint stiffness[35,73]. Leg stiffness is the most appropriate to measure and assess the dynamic and multiplanar characteristics of the whole lower limb during running or walking[48,49]. There are many different methods to calculate leg stiffness including the one-dimensional, two-dimensional, and three-dimensional method[49,50,90]. In this study, the three-dimensional leg stiffness equation will be utilized. Leg stiffness has been incorporated to optimize functional performance and explore injury mechanisms during many different sports tasks[34]. Some of these studies have been conducted outside laboratory settings to evaluate the role of surface stiffness and how athletes respond. However, the evaluation of how healthy adults use leg stiffness to maintain their gait patterns by simulating uneven surfaces during real world walking is still yet to be observed. The stimulus of surface stiffness being different between limbs during gait is important to accurately represent and emulate human walking for real world applications. This may give insight into the gait patterns that change due to external stimuli (i.e. walking on grass or pavement) and possible comparison to adaptations of internal stimuli, such as musculoskeletal or neurological pathologies.

Methods

Twenty healthy individuals between the ages of 18 and 40 were enrolled in this study and recruited from Virginia Tech. To be eligible for this study, the individual could not have chronic back pain, history of any major lower extremity surgery or injury, or a self-reported current or recent lower extremity injury reported within the last 2 months that limited physical activity for more than two days. In addition, participants had to be able to walk unassisted for 30 minutes. Due to shoe sizes available in the lab, participants were required to have a shoe size between 6.5 -11 for males and 7-11 for females.

Prior to data collection, the research study personnel described the study, and each participant signed institutional review board approved informed consent. Demographics including age, height, and weight were also collected prior to data collection. Participants were provided with standardized, laboratory-issued neutral cushioned running shoes (Nike Zoom Pegasus; Nike Inc., Beaverton, OR, USA) and tight fitting athletic spandex clothing. A three-dimensional motion capture system consisting of 10 cameras (Qualisys, Gothenburg, Sweden) and eight time-synced force plates (AMTI, Watertown, Massachusetts) were used to collect all biomechanical data in the Granata Biomechanics Lab. Both the cameras and force plates recorded at 240 Hz. After participants changed into the provided clothing and shoes, 43 retroreflective markers in total were placed on the participant in a modified Helen Hayes marker set[82] (Figure 3). The markers consisted of 27 individual markers placed at the 1st metatarsal, 5th metatarsal, lateral heel, superior heel, inferior heel sacral, greater trochanter, the medial and lateral malleolus and femoral epicondyle, anterior superior iliac spine, and the posterior superior iliac spine. In addition, four clusters of four markers that were wrapped around each thigh and shank.

Figure 4: Marker Placement: a) Male Anterior View, b) Male Posterior View

A lower extremity modified Helen Hayes marker set was used[82]. Following placing the markers, a five second standing trial was recorded. This trial was used to calculate anatomical axes and joint centers to create a three-dimensional skeletal model. The 1st metatarsal, 5th metatarsal, medial femoral epicondyle, and medial malleolus markers were taken off following the static trial. Two types of surfaces were simulated, a “compliant” surface and a “stiff” surface. The stiff surface was made of nylon with a density of 3 pounds per cubic foot. The pressure to compress the foam 25% is 28 psi. The compliant surface was made of polyurethane with a density of 2 pounds per cubic foot. The pressure to compress this foam is 1 psi. The foam pieces were 60x60 cm each with some pieces that were split in half to make 60x30 cm pieces to be placed on the force plates. Two surface stiffness condition set ups were observed for this study consisting of the control and the side-to-side difference condition shown in Figure 4.

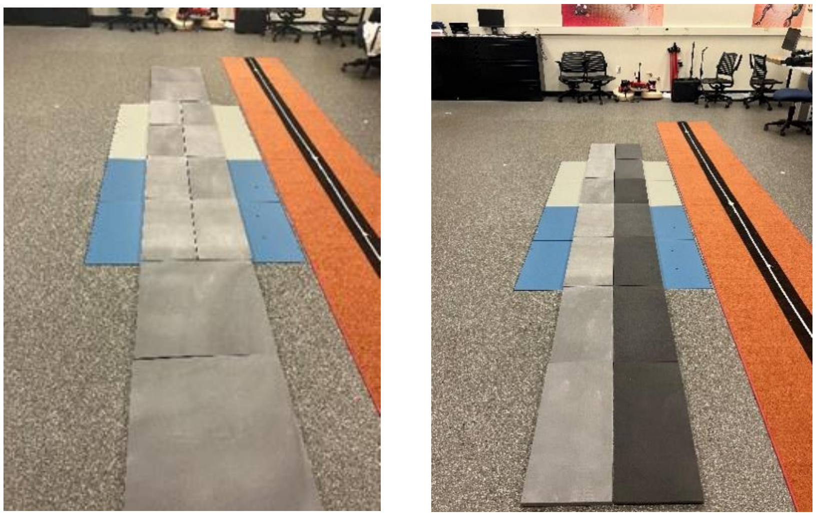

Figure 5: Two different surface stiffness conditions: Left to Right: control, side-to-side

The dark grey foam pieces were the “compliant foam”, while the lighter foam pieces were the “stiff foam”. The control set up consists of all stiff foam, while the side-to-side set up consists of stiff foam on the left and compliant foam on the right. Participants completed eight 10-meter walking trials for each surface stiffness condition. The order of the surface stiffness condition was randomized prior to beginning the walking trials. Participants were instructed to keep their eyes up as they were walking to keep them from focusing on their steps. Start locations of the participants were adjusted by the study personnel to ensure each foot contacted a single force plate. Participants were given a 20 second rest in between trials to prevent fatigue. Qualisys Track Manager (Qualisys, Gothenburg, Sweden) and Visual3D (AMTI, Watertown, Massachusetts) software were used to analyze and process all three-dimensional kinematic and kinetic data. A low pass Butterworth filter with a cut off frequency of 7 Hz and 100 Hz was used to filter all marker and force plate data, respectively. All force metrics were normalized to body weight. The data was analyzed, and the following metrics were exported from Visual 3D, GRF, HJC, COP. The HJC and the COP were used to calculate the three-dimensional leg length[50]:

$$L_{3D} = \sqrt{(HJC_z - COP_z)^2 + \left(HJC_y - COP_y\right)^2 + (HJC_x - COP_x)^2}$$

The three-dimensional leg length and the peak resultant GRF was used to calculate the leg stiffness:

$$k_{leg} = RGRF_{max} \cdot \Delta L_{3D}{}^{-1}$$

The exported text files and the three-dimensional leg stiffness equation were put into a custom-built MATLAB (MathWorks, Natick, MA) code to calculate leg stiffness NSI during the weight acceptance phase of the second and third consecutive steps on the force plate. If these steps could not be used, then the first two or last two steps were used. The NSI values were calculated using a minimum of three trials[23]:

$$NSI = \left(\frac{X_{Compliant,t} - X_{Stiff,t}}{max_{t=1:n}\left(\max\left(0, X_{Compliant,t}, X_{Stiff,t}\right)\right) - min_{t=1:n}\left(\min\left(0, X_{Compliant,t}, X_{Stiff,t}\right)\right)}\right) * 100$$

The leg used to step on the compliant foam was used as the dominant leg in the NSI calculation using the assumption that the compliant foam would impel a greater limb stiffness value. For consistency purposes, the right leg was considered the dominant leg in the NSI calculation for the control condition. An NSI value of ±100% is the maximum level of asymmetry and a NSI value of 0% indicates perfect symmetry. Lasty, a positive NSI value indicates the compliant foam had greater leg stiffness.

All statistical tests were completed in JMP (SAS Institute Inc., Cary, NC). An analysis of variance (ANOVA) test was used to determine if average walking speed was significantly different between conditions. To determine the differences in limb stiffness NSI values between the two conditions (side-to-side and control), a linear mixed effect model was used.

Results

Twenty participants between the ages of 18 and 40 participated in this study. The average age, weight, and height of the participants was 23yrs ± 4yrs, 69.3kg ±10.7kg, and 1.67m ±0.09m, respectively. The average walking speed (*p*=0.762) and the limb stiffness NSI (*p*=0.244) were insignificant between conditions shown in Table 2.

Table 2. Mean and standard deviations for Gait Speed and Limb Stiffness NSI by condition

	Control	Side-to-Side	*p*-value
Gait Speed (m/s)	1.16m/s ±0.11m/s	1.15m/s ±0.10m/s	0.762
Limb Stiffness NSI	16.4 ±2.1	12.2 ±2.1	0.244

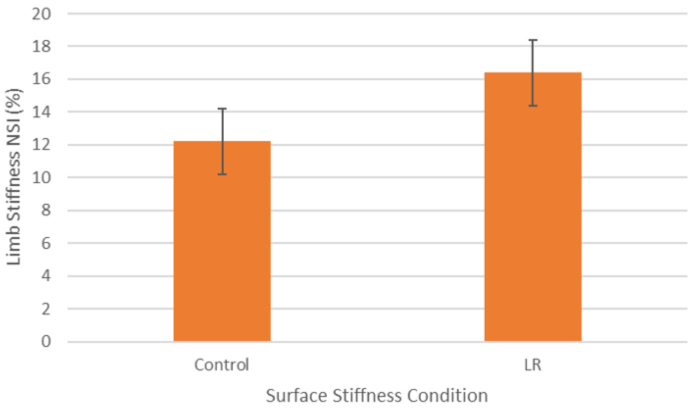

Figure 6: Mean limb stiffness NSI values for the control and side-to-side surface stiffness conditions

Discussion

The goal of this study was to determine how limb stiffness symmetry changes when surface stiffness is different side-to-side between limbs during walking. Assessing limb stiffness symmetry and surface stiffness is important to understand how humans adjust to imbalances and instability. The hypothesis was that limb stiffness symmetry would be significantly reduced when surface stiffness was different between limbs. The limb stiffness NSI values were not significant between the two conditions (side-to-side, control). Thus, the results did not support the hypothesis.

This may be due to the ability of healthy adults to overcompensate for the difference between limbs. The participants also might've been anticipating and easily adjusting to the uneven surface by the time the measurement on the force plate was taken. The results did not agree with what was expected from previous literature that observed changes in limb stiffness and symmetry on different surfaces[52,67]. Therefore, additional research is warranted to bridge the gap of how humans compensate on uneven surfaces using limb stiffness during walking.

However, this study was able to simulate uneven terrain in the real world which is beneficial to improve injury prevention and reduce the energy costs associated with walking on uneven surfaces[53]. Since walking on uneven terrain requires more mechanical work performed by the body than smooth ground walking, this research is beneficial to learning what factors contribute to this[53]. This study also addresses how humans compensate for instability and imbalances that occur from walking on these types of surfaces or from disorders. This is beneficial to emulate human walking in the real world. It is also essential to prevent injuries that could occur in hikers or everyday walking on different types of surfaces in healthy and clinical populations. Future studies could incorporate more drastic surface changes and investigate other measures that humans use to adapt to uneven terrain during walking, such as joint stiffness, muscle activation, joint work, and joint excursions. Lastly, future studies could also use this research as a comparison to investigate compensatory patterns on different surface stiffness conditions in stroke patients, osteoarthritis patients, people with musculoskeletal and neurological disorders, and other clinical populations.

A limitation of this study was the smaller sample size. A bigger sample size may have shown more differences between conditions for the limb stiffness NSI. Another shortcoming was the fact that participants' starting position was already on the uneven surface which may have led to a quick adjustment before the measurements that were taken on the force plates. In addition, the learning curve associated with walking on the uneven surfaces could have affected the results as well. Participants may have learned how to modify their walking to maintain their balance as the trials went on. It was also challenging to be able to capture how fast participants were able to adjust because of the small number of steps that could be taken on the force plates. Capturing more steps may have allowed us to see the learning curve and how much it may have affected the results. In addition, the standardized shoes that were provided may have affected the way participants adjusted to the different surfaces. This is because there is a level of compliancy within the shoes themselves. Testing barefoot may have allowed for more accurate results of how limb stiffness symmetry is impacted on the surfaces. Lastly, results from this study can only be concluded for these specific types of foams. Other types of surfaces could be used to observe the change in limb stiffness symmetry. This work was able to simulate uneven surface during real world walking. This is essential to further understand how humans modulate leg stiffness to maintain stability on when surface is different between the left and right limb. This also has implications on adjusting to imbalances due to movement disorders or conditions that affect mobility.

Ch. 4 Conclusion

Assessing how an individual adjusts to changes in surface stiffness during walking will provide an improved understanding of limb stiffness symmetry pertaining to injury. The first goal of this work was to determine how limb stiffness symmetry changes when transitioning to surfaces of different stiffnesses. The transitions consisted of the stiff to compliant foam transition and the compliant to stiff foam transition. Both conditions were then compared to the control condition. Limb stiffness NSI calculated to quantify the level of symmetry between conditions. The results revealed that limb stiffness symmetry was significantly different between the transitions and the control condition. However, there was no difference between limb stiffness symmetry of the sub-conditions showing that transition order from the different foams is insignificant. This shows that limb stiffness symmetry does change when transitioning to a different surface stiffness. This information is important to understand how humans adjust to a different surface in real world conditions.

The second goal of this work was to examine how limb stiffness changes when surface stiffness is different between limbs. These conditions consisted of the side-to-side stiffness difference and the control surface condition. The variable of interest was the limb stiffness NSI which was the index used to quantify the level of symmetry. The results showed that there was no significant difference between the side-to-side and the control condition for limb stiffness NSI. These results exhibited contradictory findings to what has been seen in previous studies that suggest limb stiffness does change depending on surface stiffness[45,52]. These absent changes could be due to overcompensation or the healthy adults being able to quickly adjust from starting the trials on the uneven surface. This is important for simulating uneven surfaces that cause humans to compensate for changes in surface and imbalances.

A limitation of the study was the small sample size. A bigger sample size may have shown more differences between the side-to-side and control conditions. Another limitation was the number of steps taken before the measurements taken on the force plate and the learning curve associated with maintaining balance on the different surfaces. Participants may have been able to adjust on the side-to-side surface stiffness difference as the trials went on. Having a longer walkway or more steps on the uneven surfaces may have allowed us to see the learning curve and how quickly participants were able to adjust. In addition, standardized lab shoes were used for the study which also have a level of compliancy that could have affected how participants used limb stiffness to compensate on the surfaces. Testing participants while barefoot could eliminate the extra compliancy coming from the shoes.

Further research is needed to observe the impact of surface stiffness on limb stiffness symmetry during walking. Future studies may benefit from taking multiple steps for measurements along the walkway to see how participants adjusted throughout the trial. Future work could benefit from a larger sample size and more trials that could possibly highlight more differences between conditions. In addition, future directions from this study could incorporate other measures such as joint work, joint stiffness, joint angles, and excursions. It may also be beneficial to look at the limb stiffness values for the individual foam panels to see exactly what was contributing to the asymmetries that were seen. Lastly, future studies could benefit from incorporating other types of contact surfaces in real world conditions, as well as using this as a basis for comparison to clinical populations.

Overall, this research is beneficial to learning the compensation methods humans use to walk on uneven surfaces or transition to different surfaces. Understanding this has important implications to how humans adapt to imbalances and instability during walking due to changes in surface stiffness or movement disorders.

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