Exploration of Movement Variability and Limb Loading Asymmetry During Simulated Daily Functional Tasks

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Abstract

The human body is a complicated dynamic system that is difficult to model because of the numerous interactions that occur between limbs during various tasks. There are documented movement differences when assessing movement in various populations, for example, joint angle and loading symmetry differences when comparing a clinical and healthy population. Symmetry deficits can impact quality of life and in some cases have been associated with an increase in injury risk. Therefore, it is essential to understand movement and loading symmetry in healthy individuals to facilitate the identification of rehabilitation targets. The purpose of this research was to assess the impact that task type and sex have on movement variability and load symmetry in healthy younger adults. The tasks included in this study represent activities of daily living such as level walking, stair ascent, stair descent and standing up from a chair. A wireless, single-sensor in-shoe force sensor allowed for data collection in a non-laboratory setting so that peak impact force and average loading rate could be evaluated across the different daily tasks. To assess movement variability, the coefficients of variation (CV) were determined for each task. The peak impact force (PIF) did not show a significant interaction between sex and task ($p=0.627$) or between sexes ($p=0.685$). The PIF did show significant between-task differences ($p < 0.001$), where the highest mean CV was observed in the sit-to-stand task and the lowest CV was observed during level walking. The variation between movements could be a result of the differential motor skill required to perform the task. The average loading rate (ALR) did not show a significant interaction between sex and task ($p=0.069$) or between sexes ($p=0.624$). The average loading rate showed significant between-task differences ($p < 0.001$), where the highest mean CV was observed in the sit-to-stand task and the lowest CV was observed during level walking. Based on these results, differences in movement type needs to be considered when evaluating average loading rate. To assess the impact of task type on load symmetry, the absolute symmetry index was calculated for the peak impact force and the average loading rate. For both parameters, only between task differences were identified ($p < 0.001$) and further analysis showed that sit-to-stand was significantly different from the other three movement tasks. The acceptable threshold for a healthy level of asymmetry has been defined in a clinical population to be less than 10%. Based on a chi square analysis, the 10% threshold accurately represents 95% of the population when used to measure peak impact force in level walking, stair ascent and stair descent. However, when assessing peak impact force symmetry during sit-to-stand or assessing average loading rate symmetry between tasks, the 10% threshold does not consistently represent 95% of the population. These results indicate that a threshold for a healthy symmetry may need to be redefined for bilateral movements and that the symmetry threshold may need to be specific to the outcome measure of interest.

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General Audience Abstract

When an individual completes a task there are many options for how they accomplish the movement each of which requires the different use of motor skills, these differences in how tasks are completed are called movement variability. A better understanding of these movement differences during various tasks in a healthy population then could help prevent long term injury and allow for the development of interventions to aid in recovery following injury. One way to assess measurements of the human body is to look at symmetry. Movements that are performed on a daily basis include walking, stair ascent, stair descent and standing up from a chair are considered activities of daily living throughout literature. Therefore, it is important to simulate these daily activities to assess a healthy population. Thus, this research aims to assess the impact that the type of task being completed has on the variability of movement and load symmetry in a healthy young adult population. Data collection was performed with an in-shoe measurement device that connects via Bluetooth to an iPad. These sensors allow for data to be collected outside of a laboratory setting allowing for the collection of a wider variety of tasks.

The coefficient of variation (CV) was calculated for each task. This is a measure that allows for an understanding of the standard deviation of a measure in relation to the mean of the data. Differences in peak impact force and average loading rate variability were observed between tasks. For both parameters, the sit-to-stand task had the largest variability, most likely due to this being a task that allows for the use of limbs, which provides individuals with more flexibility in how they complete the movement.

To assess load symmetry between tasks, the absolute symmetry index was calculated, a value that computes a percent difference between the right and left limbs. The peak impact force symmetry of the sit-to-stand task was different from the others because it requires the loading of both limbs simultaneously, which allows individuals to preferentially load one limb versus the other when completing this task. When evaluating load symmetry, clinicians have been using a threshold of 10% when defining a healthy symmetry benchmark when evaluating injury recovery. A difference greater than 10% between limbs may suggest a higher susceptibility to injury or a lack of recovery. This study evaluated if this 10% threshold accurately represents symmetry in peak impact force and average loading rate for 95% of the participants. While the 10% threshold does accurately describe the between limb differences in walking, stair ascent and stair descent tasks, the 10% threshold does not represent the results from 95% of those in this healthy population when standing up from a chair. Further, this 10% threshold did not accurately describe the symmetry discrepancies in average loading rate for any task evaluated in this study. These results suggest that a benchmark for defining healthy symmetry may need to be redefined for some tasks and outcome measures.

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List of Abbreviations

ALR	Average Loading Rate
ANOVA	Analysis of Variance
ASI	Absolute Symmetry Index
ASIS	Anterior Superior Iliac Spine
BW	Body Weight
CV	Coefficient of Variation
GRF	Ground Reaction Force
LAP	Load Analysis Program
ICC	Interclass Correlation Coefficient
PIF	Peak Impact Force
SI	Symmetry Index

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Ch. 1 Introduction

Background

Symmetry is defined as an equal balance among systems or parts of a system. Symmetrical movements of the human body are important for safe and efficient movement during activities of daily life. For the last several decades, symmetry has been studied to better understand locomotion and provide normal standards and baselines of gait for use when assessing age-related diseases and the impact they have on walking performance.[1,2] Symmetry has played an essential role in understanding recovery during the rehabilitation process in clinical populations including those who have suffered a stroke[3], had an anterior cruciate ligament reconstruction[4], hip replacement[5], total knee arthroplasty[6], and who suffer from hip osteoarthritis[7].

Initially it was believed that able-bodied humans performed symmetrical movements. However, observed variability in locomotion suggests that asymmetrical movement is present in healthy populations. Sadeghi et al. examined lower-limb locomotion within a healthy population to understand the differences in muscle power between limbs and to determine which limb, dominant or non-dominant, drove forward propulsion and locomotor control during gait.[8] This study encouraged other researchers to explore kinetic and kinematic symmetry parameters during other movement tasks. For example, Radzak et al. concluded from 20 healthy adults that limb asymmetry is apparent during running gait in the outcome measures of interest in their study.[9] In addition to biomechanical parameters assessed using three-dimensional motion capture, asymmetries in a healthy adult population have been identified through biplane radiography.[10]

Research has determined the impact of injury on movement symmetry[4,11], as well as exploring methodological questions about the quantification of symmetry.[12–14] Symmetry has been quantified for decades[15] using a variety of methods such as comparisons across gait cycles[16,17], angular measurements[18], and using direct statistical comparisons between limbs[19]. There have been many symmetry metrics described in the literature. The Ratio Index (RI)[20] was proposed by Ganguli et al. in 1974. This work investigated differences during the gait cycle in a below-knee amputee population. The RI calculates an index of symmetry using the ratio of the values for the two limbs and expresses the result as a percent as shown in Equation 1.1.[20]

$$RI = \left(1 - \frac{X_R}{X_L}\right) * 100\% \tag{1.1}$$

For this study specifically, X_R was the peak of instantaneous velocity of the right limb and X_L was the peak instantaneous velocity of the left limb, where RI = 0% is perfectly symmetric. The RI, however, has been shown to be overly sensitive to small values in the denominator[21], thus there was a need to quantify symmetry in another way. In 1987, Robinson et al. proposed the Symmetry Index (SI)[22] to quantify changes in symmetry in a population of patients with sacroiliac dyskinesia before and after treatment sessions as shown in Equation 1.2.

$$SI = \left(\frac{2 * (X_n - X_i)}{X_n + X_i}\right) * 100\% \tag{1.2}$$

Xn is the value of a variable obtained from the non-injured side and X_i is the value of a variable obtained from the injured side. Perfect symmetry was achieved when the SI equaled zero for a given variable.[22] A positive value indicated that the non-injured limb was favored while a negative value indicated the injured limb was favored for the variable of interest. In 1989, Herzog et al. expanded the SI to study asymmetries in normal human gait, modifying the equation to be values obtained from the left and right limb as opposed to non-injured and injured.[23] This index is beneficial to characterize dominance trends between the limbs, but a mix of positive and negative values can skew the averaged value of symmetry of a respective individual.[24] Thus, in 2003, Karamandis et al. modified the SI to the Absolute Symmetry Index (ASI)[24] shown in Equation 1.3.

$$ASI = \left(\frac{2 * |X_R - X_L|}{X_R + X_L}\right) * 100\% \tag{1.3}$$

Again, X_R is the value of a variable from the right limb and X_L is the value of a variable from the left limb. Similar to the SI, when the ASI equals zero for a given variable perfect symmetry is achieved. Accordingly, a positive non-zero value is the level of asymmetry of the given variable which can exceed 100%. Other common measures of symmetry and modifications to the RI used in literature include the Gait Asymmetry Index (GA)[25], the

Symmetry Angle (SA)[26] and the Normalized Symmetry Index (NSI)[21]. The GA proposed by Plotnik et al. in 2005 applies a logarithmic transformation to the ratio index as shown in Equation 1.4.

$$GA = \ln\left(\frac{X_L}{X_R}\right) * 100\% \qquad (1.4)$$

This study examined asymmetric motor performance in a patient population with Parkinson's disease[25]. In the GA, X_L and X_R are the values from the respective limbs where a negative value is possible when the value of the limb in the denominator is larger than the value of the limb in the numerator (as written above, if $X_R > X_L$).

The SA, proposed by Zifchock et al. in 2008, measures the relationship between discrete values obtained from the left and right sides of the body.[26] More specifically, this index uses angle measurements during movement from a three-dimensional motion capture system[26] to calculate a level of symmetry as shown in Equation 1.5.

$$SA = \left(\frac{45° - \arctan\left(\frac{X_L}{X_R}\right)}{90°}\right) * 100\% \qquad (1.5)$$

Similar to the other indices, a SA value of zero indicates perfect symmetry, while SA < 100% indicates a level of asymmetry.

Lastly, the NSI is a newly developed symmetry index that builds off the SI. This index reports a symmetry value that is derived from multiple trials, denoted by the subscript *t* in Equation 1.6.

$$NSI = \frac{X_{L,t} - X_{R,t}}{max_{t=1:n}\left(\max\left(0, X_{L,t}, X_{R,t}\right)\right) - min_{t=1:n}\left(\text{in}\left(0, X_{L,t}, X_{R,t}\right)\right)} \qquad (1.6)$$

This is a bounded index where NSI = 100% or NSI = -100% expresses the maximum level of asymmetry for a given variable and is used to assess symmetry in clinical populations.[21]

While the indices were each proposed to quantify symmetry in their respective research studies, they have been used to examine a variety of biomechanical parameters. The parameters of interest are specific to the population being studied as well as the task being performed. In a study by Roberts et al., the authors compared the metrics from prior research that evaluated gait in a healthy adult population to determine the most relevant biomechanical parameters for gait analysis. [27] The most commonly used parameters for gait analysis that were found to be most reliable include spatiotemporal parameters, joint angles, moments, and forces.[27]

The ground reaction force (GRF) is commonly used to assess load symmetry. In some studies, it has been measured between the foot or shoe and the ground using embedded force plates,[28,29] while in others it has been measured between the plantar surface of the foot and the shoe using in-shoe measurement systems.[30–33] In-shoe plantar loading systems allow for data to be collected in a variety of settings, including in a lab setting[34] and out of the lab[35] along with testing on various surfaces. These sensors have been validated in multiple studies[36–38] to assess loading during a variety of tasks and were found to be valid to the current gold standard, embedded force plates, and reliable across multiple days of testing. In 2017, Burns et al. tested the validity and reliability of a wireless insole, the pedoped (Novel Gmbh[39], Munich, Germany), against force plates during level walking and running.[40,41] This was a between day validity study, where the ground reaction force was collected simultaneously from wireless insoles and an instrumented treadmill at 100 Hz.[40] Interclass correlation coefficients with a 95% confidence interval were used to compare the values between the two systems. Strong agreement (ICC > 0.80) was found between the wireless insoles and the instrumented treadmill for both walking and running.[40] Since these findings were published, the pedoped system was renamed to the loadsol®.[39] In 2018, Peebles et al. evaluated the validity and between-day repeatability of the loadsol® during jumping and hopping tasks.[37] These dynamic movements require minimal restrictions to allow for the most natural movement during testing. The pedar system by Novel Electronics[39] requires the use of a backpack and lose cables to capture data as shown in Figure 1.

Figure 1: pedar® In-shoe Pressure Distribution Measurement with Backpack

Therefore the use of a wireless in-shoe sensor allows for the completion of dynamic movements without restrictions, making the single sensor loadsol® a good alternative.[37] During the validation testing, the ground reaction force was collected simultaneously using a single sensor loadsol® capturing at 100Hz and embedded force plates (AMTI, Watertown, MA, USA) sampling at 1920Hz.[37] Interclass correlation coefficients (ICCs) were used to measure repeatability between days and validity of the sensor when compared to the force plates. The ICCs were reported to be moderate to excellent for the repeatability (0.616–0.928) and validity (0.686–0.982) of the GRF measurements between the force plates and the wireless in-shoe sensors for the tasks assesses. Bland-Altman plots were also used to visually compare load measures. Based on the ICCs and Bland-Altman analysis, the authors conclude that the loadsol® is a valid and repeatable tool for evaluating kinetic measures.[37] During the validation study, a newer generation loadsol® was released, therefore, the protocol was adapted to test the effect of the sampling frequency on the validity of the loadsol® sensor during a single visit. The newer loadsol® collected at a sampling frequency of 200Hz. This increased sampling rate (200 Hz) improved the insole validity when compared to the force plate that was sampling data at 1920Hz when compared with the results from the loadsol® capturing at 100Hz. [37] Renner et al. further expanded the validation of the loadsol® through the assessment of level, inclined and declined walking and running[36] with a focus on peak force and loading rate. In this between-day study, the ground reaction force data of the 100Hz loadsol® was compared to that of an instrumented treadmill (Compact Tandem Force-Sensing Treadmill, Model: DBCEEWI, AMTI, Watertown, MA, USA) that collected data at a sampling frequency of

1440 Hz. Interclass correlation coefficients and Bland-Alman plots were used to compare force measures for level, inclined, and declined walking and running. The peak force measured by the loadsol® was reported to have strong validity and reliability when compared to the peak force measured by the instrumented treadmill (ICC > 0.8). The loadsol® with a sampling frequency of 200Hz was also used for data collection during the first visit and showed improved ICC values for peak force measurements when compared 100Hz device. Similarly, the ICC values for the loading rate were improved when capturing data at a higher sampling frequency. The loading rate measured by the 100Hz loadsol® sensors had a wider range of ICC values than the peak force across the various conditions (0.61-0.97), showing good to strong validity and reliability when compared to the instrumented treadmill. It was concluded that while the 100Hz loadsol® has excellent between day reliability for peak force measurements during the walking and running conditions accessed, the 200Hz loadsol® may be needed to measure the loading rate of more dynamic movements more accurately. It is important to understand the validity of the measurement and device to accurately characterize levels of symmetry in different tasks. While these studies[36,37,41] confirm that in-shoe force sensors can be used to measure loading during various functional tasks it is unknown if the variability of the movement performed affects the between trial variability.

Levels of symmetry have been previously characterized to identify individuals at greater risk of injury in sport and to determine when it is safe to return to sport following an injury. In Knapik et al., asymmetry was measured as an imbalance between limbs during preseason training in female collegiate athletes[12]. Injury rates were reported to be 2.6 times higher throughout the season for those with preseason imbalances of 15% or more on either side of the body (i.e., a 15% difference in the maximal isokinetic torque of the right and left knee flexors)[12]. In studies specific to return to sport after an ACL injury the proposed acceptable threshold of symmetry is 10% when taking the ratio of the injured limb to the non-injured limb. [13,14] This benchmark of a healthy level of symmetry has been used within female[12] and male[14] populations as well as across both sexes[13,14] but has not been assessed between sexes. Other research has reported differences in plantar loading[42] and pressure[43] between sexes suggesting the threshold may be different in kinetic measures between sexes. Thus, since these characterizations of symmetry were defined in specific populations, many questions about symmetry between sexes and in broader, healthy populations remain unanswered.

When considering a broader population, it is essential to assess activities of daily living as the movements are more familiar. In 2010, Kutzner [44] evaluated the loading of the knee joint between activities of daily living including level walking, stair ascending, stair descending, and standing up. These tasks have also been cited as common activities of daily living in research that has assessed trunk angles[45], joint motion[46], and the effects of exoskeleton use on movement kinematics[47]. While symmetry has been studied in these tasks individually, data has not been published about symmetry differences between the tasks within an individual.

Motivation, Purpose, and Aims

Assessing symmetry during daily activities such as walking, and stair climbing can improve our understanding of the complicated dynamic human system and the interplay between limbs. Identifying symmetry deficits during daily tasks in a younger adult, uninjured population could allow for the identification of rehabilitation benchmarks and thresholds for what would be defined as a healthy level of symmetry. Symmetry deficits have been identified as injury risk factors [9,13,27,48] and are said to decrease quality of life when these deficits are the result of muscle tightness, cartilage deterioration or bony malalignment at a joint.[49,50] It is important to determine the level of bilateral asymmetry that exists in a healthy adult population to provide a preliminary understanding for future assessment of symmetry during rehabilitation and during recovery from an injury or surgery. Therefore, the purpose of this research is to assess sex differences and the impact that movement or task type has on load symmetry measured during simulated daily functional tasks in healthy younger adults.

For the purposes of this research, healthy was operationally defined as a physically fit, uninjured, pain free, and asymptomatic participant. Additionally, a better understanding of the impact a task has on load symmetry can assist improve our understanding of how to prevent these injuries. The daily activities assessed in this study include stair ascent and descent, level walking, and sitting down and rising from a chair (sit-to-stand). These activities were selected as they have been defined as common movements for daily at home and work relevant tasks.[44–47] The measures of interest for this project based on biomechanical kinetic measures used in the field were peak impact force[4,5,28,34,51–53] and average loading rate[4,5,9], as well as peak impact force symmetry and average loading rate symmetry. The assessment of an individual's load symmetry across varying tasks will provide an improved understanding of task specific symmetry in healthy younger adults.

In this study, the Absolute Symmetry Index (ASI)[24] was used to determine significant differences in symmetry across the various tasks. The ASI is a modification of the Symmetry Index (SI)[22] proposed by Robinson et al. Research studies have demonstrated that the SI is a reliable and repeatable method for measuring symmetry across different tasks.[15,23,54] The ASI, though less common, was adapted to measure symmetry without examining limb dominance and is also a reliable method to assess load symmetry [55,56]. To our knowledge, the assessment of load and load symmetry differences has not been examined between various activities of daily living. Therefore, the ASI will be used to complete of the following aims.

Specific Aim 1: **To determine the differences in between trial kinetic variability during simulated activities of daily living (level walking, stair ascent, stair descent, sit-to-stand).**

Hypothesis: The between trial variability will not differ between the selected tasks (level walking, stair ascent, stair descent, and sit-to-stand) using a level of significance of $\alpha = 0.05$.

Specific Aim 2: **To determine differences in load symmetry (peak impact force and average loading rate) during simulated activities of daily living (level walking, stair ascent and descent, and sit-to-stand) in healthy younger adults.**

Hypothesis A: Load symmetry will not differ between level walking, stair ascent, stair descent, and sit-to-stand within an individual participant using a level of significance of $\alpha = 0.05$.

Hypothesis B: Load symmetry will not exceed 10% for any daily functional task.

Ch. 2 Between Trial Variability of an In-Shoe Force Measurement System Across Simulated Activities of Daily Living

Abstract

Introduction: Movement variability describes an individual's capacity to repeatedly perform motor skills and provides better understanding of coordination during a task.[57,58] Tasks that are observed in activities of daily living include level walking, stair ascent, stair descent, and standing up from and sitting down in a chair. Understanding the variability observed in loading metrics between these tasks will help identify motor skills that could be potential risk factors for injury. In-shoe measurement systems are an affordable and reliable way to measure force and allow for data to be collected during a variety of tasks,[36–38,43] both within and outside of a lab setting.[34,35] The goal of this work was to characterize between trial variability of peak impact force (PIF) and average loading rate (ALR) using loadsol® sensors (Novel Electronics, St. Paul. Minnesota, USA) during activities of daily living in a healthy adult population.

Methods: Seventy-two healthy adults were recruited to complete this institutional review board approved study. Participants were provided standardized running shoes and fitted with a pair of loadsol® sensors. After the sensors were calibrated using the manufactures guidelines, each participant completed the following four tasks: level walking, standing up/sitting down from a chair, and ascending and descending stairs in a randomized testing order. The coefficients of variation (CV) for the right limb[59] was calculated across the seven trials of each task in JMP (SAS Institute Inc., Cary, NC). A Shapiro Wilk test was used to check for normality ($p < 0.001$). Since the results indicate the data was not normally distributed, the ranked CV was compared between sexes and tasks using a 2×4 mixed-model repeated measures ANOVA, a level of significance set at $\alpha = 0.05$ and corresponding Tukey's Honest Significance Test post-hoc testing.

Results: For Peak Impact Force (PIF) of the right limb, there was no sex by task interaction ($p=0.627$) or a main effect for sex ($p=0.685$). All between-task differences were significant at $p < 0.001$. For the Average Loading Rate (ALR) of the right limb, there was no sex by task interaction ($p=0.624$) or a main effect for sex ($p=0.069$). All between-task differences were significant at $p < 0.001$. Since not all tasks were significantly different from one another, the Cohen's *d* was calculated to determine the effect size, where a clinically meaningful effect size is $d > 0.8$, and a low effect size is $d < 0.2$. Only the differences between sit-to-stand and the other tasks were clinically meaningful.

Discussion: For the PIF the between trial variability showed a significant difference between tasks. The walking task resulted in the smallest mean CV likely due to the need for consistent joint coordination to ensure efficient locomotion. The sit-to-stand task showed the largest mean CV because it is a bilateral loading task that allows for more flexibility throughout the completion of the movement. For ALR the Cohen's *d* effect sizes were reported to be clinically meaningful showed that the CV during sit-to-stand was significantly different from the other three tasks and that the CV for walking, stair ascent and stair descent were not statistically different from each other. This difference could be because three of the movements (walking, stair ascent and stair descent) require consistent joint coordination and are repetitive movements while sit-to-stand does not require the same coordination to complete the movement.

Introduction

Movement variability is studied in the field of sports biomechanics to better understand control and coordination during locomotion.[58] Variability shows an individual's capacity to repeatedly perform motor skills that best suit a situation or task and provides greater insight into neuromuscular control.[57] While it is commonly assumed that increased variability in a biomechanical parameter is associated with instability[60] and is often expressed as a movement challenge. Davids et al. defined variability from a dynamical systems perspective, where instead it is a "range of coordination patterns that can be used to complete the motor task".[61] In biomechanics, the variety of motor skills need for walking is different than what is needed for running, [60] hence different coordination is needed between tasks and as a result, the difference in the variability between movements is unknown. The quantification of movement variability establishes connections between the observed variations and their underlying causes[62] such as fatigue[63] and injury.[57,64] Although variability is most commonly explored in sports with more complex motor skills, it is important to understand variability during activities of daily living to provide a better understanding of observed differences and to determine if increased variability could be an injury risk factor or a measure that can be utilized when assessing recovery from an injury.

Broadly, activities of daily living are defined as routine and essential tasks that most healthy, adults can perform without assistance.[65] In biomechanical studies, activities of daily living cited in literature include level walking, stair ascending, stair descending, and standing up.[44,53] These tasks have been used to assess the effects of exoskeletons on locomotion[47], joint motion[46], trunk kinematics[45], and knee loading.[53] These studies show that motion and forces across a variety of tasks are highly activity-dependent and need to be investigated further. An improved understanding of movement variability between these tasks will provide better design considerations, rehabilitation programs, and safety regulations for injury recovery.

Another measure that is used to evaluate injury mechanisms and is important for injury prevention is asymmetry. Asymmetry is commonly assessed using limb loading.[4,5,28,34,51–53] Deficits in symmetry have been identified as injury risk factors,[9,13,27,48] thus improving our knowledge of the variability of the loading metrics used to assess movement symmetry will aid in identifying benchmarks for rehabilitation.

In biomechanics, limb loading is often assessed using the ground reaction force. [4,29,41,66–68] The current gold standard in research to assess ground reaction forces is through embedded force plates (AMTI, Watertown, MA, USA). When a participant contacts the surface, these instrumented devices measure three-dimensional force and moment. The assessment of limb loading is one of the most accurate measures due to the use of a stable, embedded force plate in the floor of a research laboratory, however, there are limitations to accessing movements in a laboratory setting. The cost and space required for the use of embedded force plates make them inaccessible for may clinical populations. Force plates have been used to assess walking[41,66], balance[67,68], jumping[29,41], and landing[4,37] as well as other movement tasks that can be completed in a laboratory setting. This technology excludes stair ascent and descent, and while instrumented stairs with force plates exist, they are expensive and not do accurately mimic the movement of ascending and descending a flight of stairs given that they include only 2-3 stairs.

Novel Electronics, Inc (St. Paul, MN) has developed the loadsol® system, a wireless in-shoe sensor that measures the normal force between the foot and the insole. The loadsol® was developed as a single sensor force measurement device that allows clinic-based assessment of load and loading symmetry. The single sensor loadsol® has been validated against the current gold standard (embedded force plates) to assess loading during level walking[36], inclined[43] and declined[43] walking, running[38], hopping[37] and jumping[37]. Peebles et al. investigated the reliability of in shoe plantar loading systems during landing tasks[37] and reported moderate to excellent validity and reliability for measures of peak impact force and loading rate in the single-hop and bilateral stop-jump.[37] This study also determined the impact of sampling rate on the collection of loading metrics with the loadsol®, and found that the loadsol® sampled at 200Hz was more accurate relative to the force plate than the sensor sampling at 100Hz. Renner et al. further validated the loadsol® to an instrumented treadmill (Compact Tandem Force-Sensing Treadmill, Model: DBCEEWI, AMTI, Watertown, MA, USA) during walking and running on a level surface, at a 10% incline and a 10% decline.[36] Again, when evaluating peak force and loading rate, the in-shoe sensors showed good to excellent validity and reliability when compared to the instrumented treadmill.[36] Renner et al. expanded on their work and assessed the interaction between age groups and genders during gait to determine if the same differences between groups were observed when using the loadsol® compared to embedded force plates.[43] During level walking, the loadsol® detected differences in peak force and loading rate that agreed with the difference detected by the force plates. Further, there was no difference reported between gender by the force plate or loadsol® during level walking, but older adults commonly had larger peak force and loading rate measurements compared to the younger adults. So, while these studies confirm that in-shoe force sensors can be used to reliably measure loading during various functional tasks, it is unknown how between trial variability differs between tasks.

The goal of this work was to characterize movement variability between tasks by assessing between trial variability using loadsol® sensors (Novel Electronics, St. Paul. Minnesota, USA) during simulated daily tasks in a healthy adult population. For the purposes of this research, healthy was operationally defined as a physically fit, uninjured, pain free, and asymptomatic. Through this work, we aim to determine between trial kinetic variability differences across simulated activities of daily living[44] (level walking, stair ascent, stair descent, sit-to-stand). The load parameters that were assessed in this study were peak impact force (PIF) and average loading rate (ALR). ALR is defined between 20% and 80% of the period between foot strike and the loading peak as the total change in force divided by the total change in time.[6] It was hypothesized that no differences in between-trial variability would exist between the four tasks using a level of significance of $\alpha = 0.05$. Furthermore, since the focus was movement variability and since asymmetry has not been reported in a healthy population, the analysis was completed only for the right limb as it represents the dominant limb in most of the population.[59]

Methods

Seventy-two healthy adults were recruited to complete this institutional review board approved study (VT IRB 21-747). Being healthy was operationally defined as being physically active, uninjured, pain free, and asymptomatic. Additionally, to be eligible to participate, individuals had to be between 18 and 30 years of age, have a shoe size between 6.5 - 11 for males and 7- 11.5 for females due to the available shoes and loadsol® sensors, and be recreationally active for at least 30 minutes three times per week. Participants were excluded if they had sustained a lower extremity injury in the previous two months, had a preexisting condition that limited participation in physical activities, had a history of major lower extremity surgery, or were pregnant.

Before each participant began the procedure, the study was described in detail and the participant signed institutional review board approved informed consent. Before completing testing, participant demographics including age, height, mass, sex assigned at birth, race, leg length and shoe size were collected and managed using REDCap electronic data capture tools hosted at Virginia Tech.[69,70] Mass was recorded from a digital scale. Leg length of the left and right limbs was measured from the anterior superior iliac spine (ASIS) to the medial malleolus with a tailor's tape measure.[71,72] This length was measured to the nearest centimeter since discrepancies smaller than this value are not clinically significant.[73,74] Participants were asked to wear their own athletic clothing and were provided standardized, laboratory-issued neutral-cushioned running shoes (Nike Zoom Pegasus; Nike Inc., Beaverton, OR, USA) consistent with their shoe size to use for testing. They were also fitted with a pair of loadsol® sensors that covered the plantar aspect of each foot and connected to the iPad via Bluetooth technology (Figure 2**)**. The sensors measure the normal force between the foot and the shoe at a sampling frequency of 200Hz.

Figure 2: loadsol® equipment

To become comfortable with wearing the insoles and to provide the needed warmup time for the insoles, participants were asked to walk around for five minutes as described by manufacturer calibration.[30] Their mass was entered in kilograms (kg) into the loadsol® application (app) on an iPad which was then converted to Newtons (N). The sampling rate was set at the sensors' maximum of 200 Hz based on recommendations from previous validation testing[36,37]. The insoles were calibrated through a series of three cycles of unloading the insoles and loading the plantar surface with the participant's full body weight in single-leg stance according to the manufacturer's guidelines. The calibration was tested by collecting a short trial of single limb standing data to determine if the loadsol® returned values within ±5% of the entered body weight. If the values were within the required range, the calibration was accepted, otherwise, the calibration procedure was repeated until this requirement was achieved.

The number of participants was determined from a pilot study. Data from five pilot participants was used to determine an effect size to, in turn, find the minimum sample size needed for the study to be powered to detect a significant difference (G*Power, Bonn FRG, Bonn University, Department of Psychology).[75] Given the following conditions, thirty-two adults were needed to power the study: a 2x4 within-between subject repeated ANOVA, an effect size of 0.217, power of 0.8, $\alpha = 0.05$, $1-\beta = 0.8$, and $r = 0.5$. To account for any lost data an additional 4 participants were included to bring the total sample to 36 participants. Sex assigned at birth was captured from each participant. Previous studies have reported that load[42] and pressure[76] differ between sexes during locomotion. Therefore, the number of participants was doubled to collect a total of 72 participants.

Each participant completed the following four tasks - level walking, standing up/sitting down from a chair, and ascending and descending stairs (Figure 3).

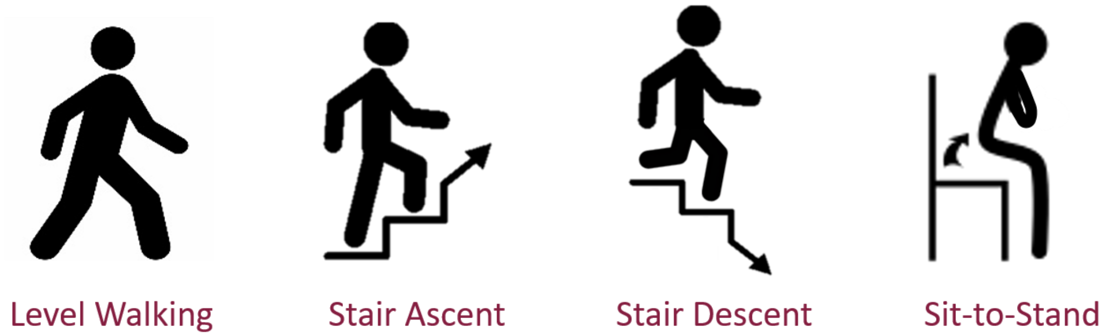

Figure 3: Simulated Daily Functional Tasks

During the walking task, participants were asked to walk 14m from one line of tape to another down a hallway (Figure 4). This distance was selected based on prior studies that analyzed gait asymmetry in healthy adult populations.[36,77] The length of the walkway was measured and marked with tape on the floor. The participant started behind the tape and began when the study member said go and simultaneously started a handheld stopwatch and time was stopped when the participant crossed the second line of tape. During each of the seven trials, walking speed and plantar loading for each step were recorded.

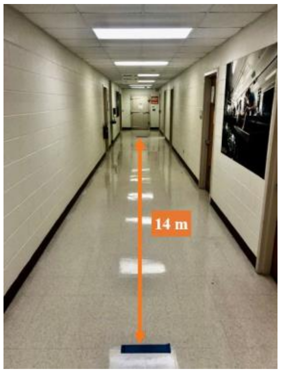

Figure 4: Experimental Set Up of Level Walking

During the stair climbing task, participants were asked to ascend and descend a flight of 13 stairs using a step-over-step technique at their desired, self-selected speed. The stair length and tread dimensions are shown in Figure 5. Given the setting and location of the study, the participant began each trial with stair ascent. When the study member said go and simultaneously started the stopwatch, the participant began ascending the stairs. Once the participant had one foot on the upper platform the timer was stopped. Once the time for that trial was recorded, the study member said go and simultaneously started the stopwatch and the participant began descending the stairs. The time was stopped when the participant made initial contact on the lower platform and the time was recorded. This was repeated for seven trials during which bilateral plantar loading was again recorded.

Figure 5: Experimental Set Up of the Stair Ascent and Descent

During the sit-to-stand task, the participant used a standard folding chair where the seat height was 45 cm off the ground as shown in Figure 6. The participant began in a seated position and was asked to cross their arms over their chest. The participant was asked to stand up and sit down seven times at a speed comfortable for them.

Figure 6: Experimental Set Up of the Sit-to-Stand

The order of tasks was counterbalanced using a Latin Squares Design using the order of participant collection. (For example, participants 1/4/7/… completed the tasks in the following order: level walking, sit-to-stand, stair ascent and descent, while participants 2/5/8/… performed the tasks as follows: stair ascent and descent, level walking and sit-to-stand, and participants 3/6/9… used this order: sit-to-stand, stair ascent and descent, and level walking). The participant received a one-minute rest between trials while data was saved. Participants were allowed to take additional rest as needed throughout testing. In addition to the rest between trial, each participant was allowed approximately a two-minute rest between conditions to allow for set-up and reduce the impact of fatigue.

All force data were normalized to body weight and analyzed using the Load Analysis Program (LAP), a custom-built MATLAB user interface that identifies individual steps using an initial contact threshold and toe off threshold.[52] The statistical analysis was completed in JMP (SAS Institute Inc., Cary, NC). A t-test was used to compare the difference in age, height, mass and task speed between the male and female participants. Then, the coefficients of variation (CV) of each parameter were calculated across the seven trials of each task. This statistical is a good measure of variability for a given parameter because it represents the dispersion of the data around the mean. The distribution of the CV was first checked for normality using a Shapiro-Wilk test. Since the assumption of normality was not met, the CV values were compared between sexes and across tasks using a 2×4 mixed-model repeated measures ANOVA on ranks. Corresponding post-hoc testing with the Tukey's Honest Significance Test with a level of significance set at $\alpha = 0.05$ were performed for significant differences. Since the order of tasks was systematic, the effect of task order was considered. These statistical comparisons were completed for the following variables: Peak Impact Force and Average Loading Rate.

Results

There were 39 female and 33 male individuals that participated in this study. A statistically significant limb difference ($p<0.001$) was identified between male and female, however, this limb length difference for each participant was less than 1cm indicating that this difference is not clinically meaningful. The female shoe size ranged between a size 7.5 and a size 10 with a mean of size 8.5 and the male shoes ranged between a size 8 and a size 11 with a mean of size 10. The average age, mass, and height are presented in Table 1 and were different between sexes, while the difference in task speed was not different between males and females.

Table 1: Participant Demographic and Task Speed Comparison (Mean ± Std. Dev.)

		Mean	Std. Dev.	p-value
Age (years)	Female	22.5	3.0	0.605
	Male	22.0	2.5	
Mass (kg)	Female	67.18	11.09	<.001*
	Male	78.75	9.82	
Height (cm)	Female	1.67	0.068	<.001*
	Male	1.79	0.075	
Limb Length (cm)	Female	0.93	0.058	0.035*
	Male	0.96	0.06	
Level Walking Speed (m/s)	Female	1.03	0.10	0.387
	Male	1.06	0.09	
Stair Ascent Speed (m/s)	Female	1.54	0.06	0.211
	Male	1.60	0.06	
Stair Descent Speed (m/s)	Female	1.46	0.07	0.094
	Male	1.38	0.10	

Peak Impact Force

A sex by task interaction was not found for the PIF ($p=0.627$). Between-sex differences in the PIF were not observed ($p=0.685$). However, between-task differences were identified ($p < 0.001$). Post-hoc testing of the coefficients of variation of the Peak Impact Force indicated that all tasks were different from one another ($p < 0.001$). The distribution and means of the coefficients of variation for PIF for each task are presented below in a Box and Whisker plot (Figure 7).

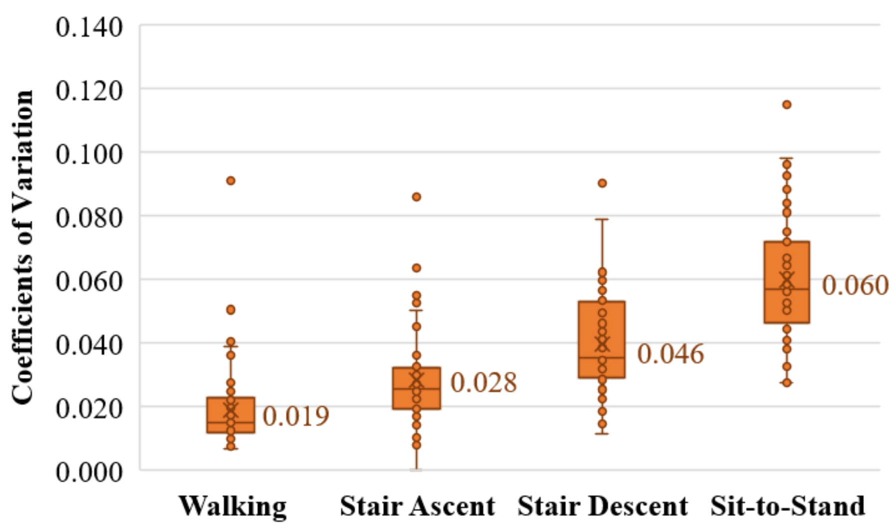

Figure 7: Average Coefficients of Variation of Peak Impact Force Across Participants

Average Loading Rate

A sex by task interaction was not found for the ALR (p=0.624) and between-sex differences were not observed (p=0.069). Between-task differences were identified (p < 0.001) . The distribution of the coefficients of variation and corresponding means for ALR for each task are presented below in a Box and Whisker plot (Figure 8).

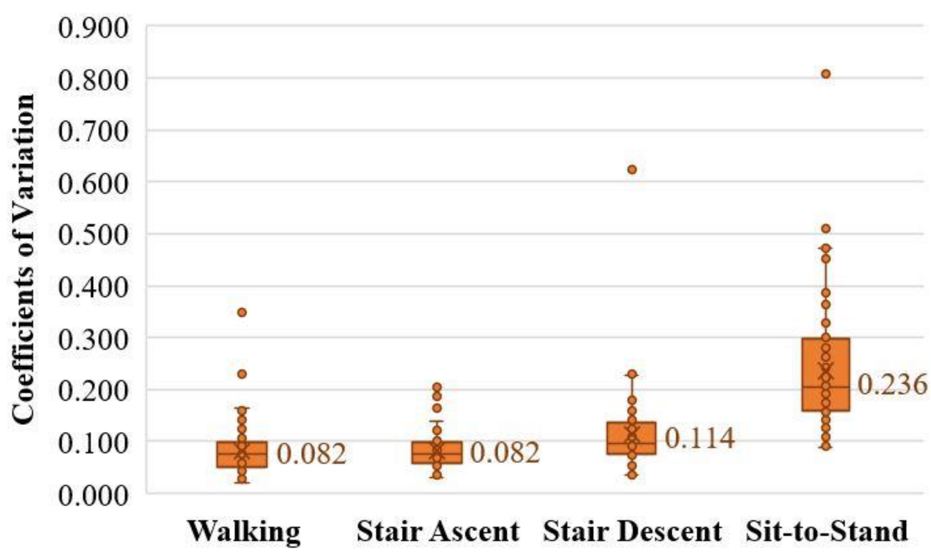

Figure 8: Average Coefficients of Variation of Average Loading Rate

To better understand the magnitude of the differences between tasks, the effect sizes as Cohen's *d* were calculated in JMP and are reported below. When $d = 0.5$, the value of the average CV for a participant in a single task is 0.5 standard deviations above the average

CV for a participant in another task.[78] A large or clinically meaningful effect size is when $d > 0.8$, while $d < 0.8$ are statistically significant, they may not be clinically meaningful.[78] Based on these results, the variability during the sit-to-stand task are the greatest as shown below in

Table 2.

Table 2: Effect Sizes of Average Loading Rate

Task Interactions		Cohen's d	P-value of Cohen’s d
Sit-to-Stand	Walking	2.248	<0.001*
Sit-to-Stand	Stair Ascent	2.157	<0.001*
Sit-to-Stand	Stair Descent	1.517	<0.001*
Stair Descent	Walking	0.731	<0.001*
Stair Descent	Stair Ascent	0.640	<0.001*
Stair Ascent	Walking	0.091	0.546

**p-value < 0.05*

Discussion

The goal of this study was to characterize differences in between trial movement variability during simulated activities of daily living (level walking, stair ascent, stair descent, sit-to-stand) when using an in-shoe force measurement device. A better understanding of variability during different tasks can help to identify potential injury risk factors as well as understanding the differences in movement control based on the movement task. It was hypothesized that the between trial variability of peak impact force and average loading rate would not differ between the assessed tasks (level walking, stair ascent, stair descent, and sit-to-stand). When assessing PIF, the hypothesis was rejected given that there was a significant difference detected between the tasks indicating the existence of differences in between trial variability between tasks.

The reported differences in PIF variability are consistent with the findings published in Stacoff et al.[79] This study evaluated differences in ground reaction forces between different ages for different tasks.[79] The authors reported that the coefficient of variability of the GRF parameters was between 0.02-0.05 and was found to be the smallest during gait.[79] The variability between movements is linked to motor skill control and the width of the base of support. The sit-to-stand task showed the largest mean CV indicating that people use more flexibility throughout the movement to complete the task. This task also requires bilateral loading, which increases the base of support providing the participant with more stability throughout the task. Walking, however, resulted in the smallest mean CV likely due to the familiarity with the movement and the need for consistent joint coordination to ensure efficient locomotion.[51]

When assessing ALR, the interaction between tasks was significantly different, therefore, we rejected the null hypothesis indicating between trial variability in average loading rate does exist between tasks. To provide a better understanding the magnitude of the significant differences observed between tasks, the effect sizes were calculated as the Cohen's *d* in JMP. The difference between sit-to-stand and the other three tasks reported Cohen's *d* values great than 0.8 that were significantly different ($p < 0.001$). Level walking, stair ascent and stair decent did not have effect sizes that were clinically meaningful, therefore. This is potentially due to the fact these three tasks are repetitive, cyclic movements[58], thus the forward locomotion of the participant throughout the task follows a repeated pattern allowing the motion to become more efficient and repeatable. Additionally, there were no significant differences in speed detected during these tasks indicating the movement consistency between the trials. The sit-to-stand task, however, is not repetitive because there is a defined start and stop to the movement and the movement is not performed in a fluid motion.

These results provide a better understanding of the movement variability that exists between tasks. For example, just because the variability of stair descent is larger than the variability during level walking this does not indicate that the sensors was less reliable when measuring stair descent, it is simply an indication of differences in how participants choose to complete movement tasks. A limitation of this study is that all of the participants were young adults. Literature shows that motor readiness and joint coordination are decreased in an elderly population and therefore the movement variability during these various tasks may be different when assessed in an older population.[80] Hence, future work should expand on Stacoff et al.'s findings to further evaluate age related differences in loading and movement variability. Any differences in variability based on age and task could help in our understanding of the impact of age and type of movement on injury risk as well as mechanisms of injury.

Ch. 3 Limb Loading Asymmetry During Simulated Daily Functional Tasks

Abstract

Introduction: Symmetry has been studied over the past few decades to provide baselines of movement to use when assessing age-related diseases and for injury prevention and rehabilitation. While symmetry is commonly measured in clinical populations, assessing symmetry during simulated daily activities in a healthy, young adult population could allow for the identification of thresholds for what would be defined as a healthy level of symmetry. The goal of this work is to assess the impact that task type has on load symmetry measured with an in-shoe load measurement device in healthy adults. The daily activities assessed in this study include stair ascent and descent, level walking, rising from a chair (sit-to-stand).

Methods: Seventy-two healthy individuals that met eligibility criteria were recruited and completed this institutional review board approved study. Participants were provided with standardized running shoes consistent with their shoe size to use during testing and fitted with a pair of loadsol® sensors that were calibrated using the manufacture's guidelines. Then, participants completed four daily functional tasks in a randomized order. The tasks included level walking, standing up from a chair, and ascending and descending stairs. The Absolute Symmetry Index (ASI) was calculated for the peak impact force and the average loading rate across the seven trials of each task. A Shapiro-Wilk test was used to check for normality, and then a 2×4 mixed-model repeated measures ANOVA on ranks and corresponding Tukey's Honest Significance Test post-hoc testing was completed in JMP (SAS Institute Inc., Cary, NC) to assess differences between tasks and sex. A chi squared goodness of fit test was used to determine if the clinically accepted 10% asymmetry level was a good representation of the level of symmetry across the four daily tasks.

Results: For the Peak Impact Force (PIF) ASI, there were no sex by task interactions ($p = 0.347$) or sex differences ($p=0.128$) observed. A between task difference was identified ($p < 0.001$) and post-hoc testing indicated that the sit-to-stand task had a clinically meaningful significant difference from each of the other tasks ($d < 0.8$), while the other three tasks did not. For the PIF ASI, the chi squared value was calculated across the three similar tasks to be $X^2= 0.281$ ($p=0.869$). For the Average Loading Rate ASI, there were no sex by task interactions ($p = 0.448$) or sex differences ($p=0.213$) observed. For the ALR ASI, again, the sit-to-stand task reported a clinically meaningful difference when compared to the other three tasks. However, for the ALR ASI, the chi squared value was calculated across the three similar tasks to be $X^2= 42.68$ ($p< 0.001$).

Discussion: For the PIF ASI, the significant difference between the sit-to-stand task and the other movement could be due to the bilaterally of the task, which would allow for differential limb loading during the completion of the task. Also, for PIF ASI, since the chi squared value was less than the critical value ($X^2= 0.281 > 5.99$, at $\alpha = 0.05$ and 2 DoF), the 10% threshold that is indicative of "healthy asymmetry" does represent 95% of the population during level walking, stair ascent and stair descent. Given the chi square value is above the critical value for during the sit-to-stand task, this indicates the potential need to redefine a healthy benchmark of symmetry during certain activities of daily living.

Introduction

For the last several decades, symmetry has been studied to better understand the impact that injury has on movement symmetry[4,11] and to provide normal standards and baselines of gait for use when assessing age-related diseases[3,7] as well orthopedic surgery and rehabilitation[5,6]. Although it was initially believed that able-bodied humans performed movements symmetrically, observed differences in speed, motor skill complexity, and muscle power between limbs suggested that asymmetrical movements are present in a healthy population.[8,9,81,82]

Over the last few decades, understanding movement symmetry has provided clinicians with a threshold to assess injury recovery and rehabilitation in clinical[3–7] and athletic[12,57,61,66] populations. The current acceptable threshold of symmetry is 10% when taking the ratio of the injured limb to the non-injured limb.[7,13,14] This benchmark has been accepted within specific populations. It has been validated as a cutoff in clinical settings for assessing gait in age-related diseases[7] and as a clinical discharge criterion for athletes to return to sport after injury.[14] However, this is an arbitrary guideline, and hence, many questions about symmetry in broader, healthy populations remain unanswered. Identifying symmetry deficits in an uninjured population will help to evaluate if this threshold accurately represents the level of asymmetry observed in a healthy population. Further, classifying this benchmark will provide a control comparison that can be used when evaluating symmetry changes in clinical populations such as those affected by a stroke[83] or osteoarthritis.[84]

Researchers have developed a number of measures that allow for the quantification of symmetry[12–14] including methods such as comparisons across gait cycles,[16,17] angle measurements,[18] and statistical comparison.[19] The Ratio Index (RI)[20] was proposed over four decades ago to analyze gait symmetry and is calculated as a symmetry index using the ratio of the values for the two limbs. A shortcoming of this index is that it is sensitive to small numbers in the denominator,[8,21] but, it has served as the template for other symmetry indices. Common measures of symmetry and modifications to the RI used in literature include the Gait Asymmetry Index (GA)[25], the Symmetry Angle (SA)[26] and the Normalized

Symmetry Index (NSI)[21]. The most popular, the Symmetry Index (SI), was proposed by Robinson et al..[22] This index was first used to quantify changes in symmetry in a clinical population and was adapted by Herzog et al. to study symmetry in normal human gait.[23] The SI value reported indicates the level of symmetry, where SI = 0% indicates full symmetry and both SI > 100% and SI < -100% indicate full asymmetry. While the SI can characterize dominance trends between the limbs by the sign of the SI value returned, the presence of positive and negative values skews the average value of symmetry of a respective individual.[24] Thus, in 2003, Karamandis et al. modified the SI to the Absolute Symmetry Index (ASI)[24] to quantify symmetry without assessing limb dominance.

While a variety of kinetic and kinematic symmetry parameters can be evaluated using the ASI, one measure that is often assessed is limb loading.[15,18,34,85] Symmetry deficits have been identified as injury risk factors [9,13,27,48] and are said to decrease quality of life when these deficits are the result of muscle tightness, cartilage deterioration or bony malalignment at a joint.[49,50] Quantifying the level of bilateral load asymmetry in a healthy adult population and understanding the effect of different movements on symmetry could improve our understanding of these injuries and potentially allow for the develop of training and intervention programs. Commonly performed activities of daily living that have been previously studied include level walking, stair ascending, stair descending, and standing up.[44–47] These tasks have been used in prior studies because they are movements familiar to participants and provide variability in joint motion.

Previous studies have reported that the load[42] and pressure[76] beneath the foot differ between sexes in during locomotion. Therefore, the primary objective of this study was to assess the impact that movement or task type had on load symmetry measured with an in-shoe load measurement device during daily functional tasks in both healthy males and females. Through this work, we aim to determine differences in load symmetry during a series of simulated daily functional tasks[44] (stair ascent and descent, level walking and sit-to-stand) in healthy younger adults. Our hypotheses were that load symmetry would not differ between sexes and across the four tasks of interest (level walking, stair ascent, stair descent, and sit-to-stand) and that load symmetry (peak force and loading rate) would not exceed 10% for any daily functional task in more than 95% of the sample.

Methods

Seventy-two individuals, between the ages of 18 and 30 years, were recruited from Virginia Tech (IRB 21-747). To be eligible to participate, the individual could not have a history of any major lower extremity surgery, have a preexisting condition that limited involvement in physical activities, or be pregnant. The eligibility criteria also stated that participants were recreationally active for at least 30 minutes three times per week and that they had not experienced a lower extremity injury within the past two months that limited activity for more than two days, thus representing a healthy population. For the purpose of this study, healthy was operationally defined as being uninjured, asymptomatic, pain free, and physically active.

Prior to beginning data collection, the study procedure was described by the study personnel and each participant signed the institutional review board approved informed consent. Then demographic information was collected and managed using REDCap, an electronic data capture tools hosted at Virginia Tech.[69,70] Each participant was asked their age, sex assigned at birth and self-identified race. Additionally, the shoe size worn during testing was recorded. From the standardized shoes available in the lab and the available loadsol® sensors, females were required to have a shoe size of 7-11.5 and males were required to have a shoe size between 6.5-11. Other information included height, measured using a tape measure on the wall when the participant was standing straight with their back again the wall to the nearest 0.01m, and mass, measured from a digital scale to the nearest 0.1kg. A tailor’s tape measure was used to assess limb length which was measured from the anterior superior iliac spine (ASIS) to the medial malleolus to the nearest centimeter for the left and right limb [71,72] Studies have reported that limb length discrepancies smaller than 1cm are not clinically meaningful.[73,74]

Participants were provided with standardized, laboratory-issued neutral-cushioned running shoes (Nike Zoom Pegasus; Nike Inc., Beaverton, OR, USA) and fitted with a pair of loadsol® sensors consistent with their shoe size to use for testing. These sensors covered the plantar aspect of each foot and measured the normal force between the foot and the shoe. These single sensor insoles connect via Bluetooth to an iPad and are used with the loadsol® application (app) from the Apple Store (Figure 9).

Figure 9: loadsol® equipment

To accurately calibrate the sensors, participants were asked to walk around for five minutes, which allowed them to become comfortable with wearing the loadsol® sensors and adjust their shoe size if necessary. Their mass in kilograms (kg) was entered into the loadsol® application (app) and converted into Newtons (N). The sampling rate was set at to 200Hz, which is the maximum sampling rate of the single-sensor loadsol® and was recommended based on previous validation studies.[36,37] The insoles were calibrated through a series of unloading and loading cycles of the loadsol® sensors during single-leg stance. This was followed by the collection of a short trial of single limb standing to determine if the force detected was within ±5% of the participant's full body weight. If the values from the loadsol® were not within this range, the calibration was repeated. An example of this calibration can be viewed here: https://www.youtube.com/watch?v=4-VfQEUR9iw.[30]

To determine the minimum sample size needed for the study, five participants completed a pilot study. Data collected from these participants was used to calculate the effect size ($f = 0.217$). Using a 2x4 within-between subject repeated ANOVA, G*Power (Bonn FRG, Bonn University, Department of Psychology)[75] was used to calculate the number of people required to power the study to 80% and detect a significant difference. The other conditions used to determine the needed sample size included $r = 0.05$, $1\text{-}\beta = 0.8$, and $\alpha = 0.5$ and resulted in a target sample size of 32. The total sample was increased to 36 participants to account for equipment malfunctions during collection or lost data. Additionally, this study evaluated differences between sexes, therefore, to collect both males and females the total sample was doubled to 72 participants.

There were four tasks observed in this study: level walking (W), standing up/sitting down from a chair (S2S), and ascending (SA) and descending (SD) stairs. Each participant completed every task in a randomized order using a Latin Squares Design based on their participant number (Participants 1, 4, … W, SA, SD, S2S, Participants 2, 5, … SA, SD, S2S, W, and Participants 3, 6, … S2S, W, SA, SD). There were seven trails recorded for each task and the resting time between each trial was roughly 60 seconds. Participants were encouraged to ask for a longer rest period as needed.

Based on prior studies that analyzed gait asymmetry in healthy adult populations, the walkway distance was measured to be 14 meters.[36,77] This length was marked with tape on the floor at either end of the hallway allowing the participant to start in a consistent location (Figure 10). They began to walk at a self-selected speed when the study team member said go and simultaneously started a handheld stopwatch and the loadsol® app. When the participant reached the second line of tape, the timer and loadsol® app were stopped. This task was repeated for seven trials.

Figure 10: Walking Task

During the stair climbing task, the participant was asked to ascend and descend a flight of 13 stairs using a step-over-step technique as shown in Figure 11. Stair dimensions were measured to be 30 cm in length and 17.5 cm in tread height. Due to the location of the stairwell used in this study, the participant began the stair task with stair ascent for each trial. When the study member said go and simultaneously started the stopwatch and the loadsol® app, the participant began ascending the stairs at their desired, self-selected speed. Once the participant had one foot on the upper platform the timer and loadsol® app were stopped and the participant waited for the study member to record the time for the trial. The participant began descending the stairs when the study member said go and simultaneously started the stopwatch and loadsol® app. Again, the timer was stopped when the participant first made contact on the lower platform. This was repeated for seven trials.

Figure 11: Stair Ascent and Descent Task

A folding chair with no arm rests and a seat that was 45 cm off the ground was used for the sit-to-stand task. The participant was asked to cross their arms over their chest as shown in Figure 12Figure 6. They began in a seated position and were asked to stand and sit down seven times at a comfortable, self-selected speed after the study member started the loadsol® app. A handheld stopwatch was not used to record time for this task because there is no horizontal distance covered and the loadsol® app records the force as a function of time that can be used to calculate the average loading rate.

Figure 12: Sit to Stand Task

The Load Analysis Program (LAP), a custom-built MATLAB user interface, was used to normalize all force data to body weight and identify individual steps.[52] The first two and last two steps during the walking, stair ascent and stair descent trial were removed since they tend to be different due to the speeding up and slowing down at the beginning and end of each task. The initial contact threshold and toe off threshold was set to 50 N for each task.[52] Loading measurements from the loadsol® during stair ascent and descent, level walking and sit-to-stand were used to calculate the Absolute Symmetry Index as shown in Equation 3.1:

$$ASI = \left(\frac{2 * |X_R - X_L|}{X_R + X_L}\right) * 100\% \qquad (3.1)$$

JMP (SAS Institute Inc., Cary, NC) was used to complete the statistical analysis. To compare the difference in age, height, mass and task speed between males and females, an independent sample t-test was used for each parameter. Then, the ASI of the peak impact force (PIF) and average loading rate (ALR) was computed across the seven trials of each task. Using a 2×4 mixed-model repeated measures ANOVA, the ASI of the peak impact force (PIF) and the average loading rate (ALR) were compared between sexes and across tasks (level walking, stair ascent, stair descent, sit-to-stand). If a significant difference was observed, post-hoc testing was completed using Tukey's Honest Significance Test. In addition, to determine if a threshold is a good representation of a population across different categories. Thus, a chi squared goodness of fit test was used to analyze if the ASI exceeded 10% for any daily functional task. The chi squared (X^2) equation is presented in Equation 3.2,

$$X^2 = \sum_{i=1}^{n} \left(\frac{(O_i - E_i)^2}{E_i}\right) \qquad (3.2)$$

where n is the number of groups, O_i is the observed frequency of success in a specific task (i.e. 90% of participants are under the 10% threshold), and E_i is the expected frequency of success (i.e. we assume the 10% threshold is true for 95% of any given healthy population).

Results

Thirty-nine female participants with a mean age of 22.5 ± 3.0 years and thirty-three male participants with a mean age of 22.0 ± 2.5 years completed this study. The average height and mass of the female (n=39) participants was 1.68m ± 0.07m and 67.2kg ± 11.1kg and of the male (n=33) participants was 1.79m ± 0.08m and 78.8kg ± 9.8kg. The shoe size for the female participants was on average 8.5 and ranged between a size 7.5 and a size 10. Similarly, for the male participants the average shoe size was 10 and ranged between a size 8 and a size 11. The differences between males and females for the height ($p < 0.001$), mass ($p < 0.001$), and shoe size ($p = 0.035$). were found to be statistically significant. The limb length inequality for all participants was less than 1cm.

Peak Impact Force Symmetry

No sex by task interaction ($p = 0.347$) or main effect for sex ($p=0.128$) was found for the Peak Impact Force Absolute Symmetry Index (PIF ASI). There was a significant main effect for movement task ($p < 0.001$). The distribution and means of PIF ASI for each task are presented below in a Box and Whisker plot (Figure 13).

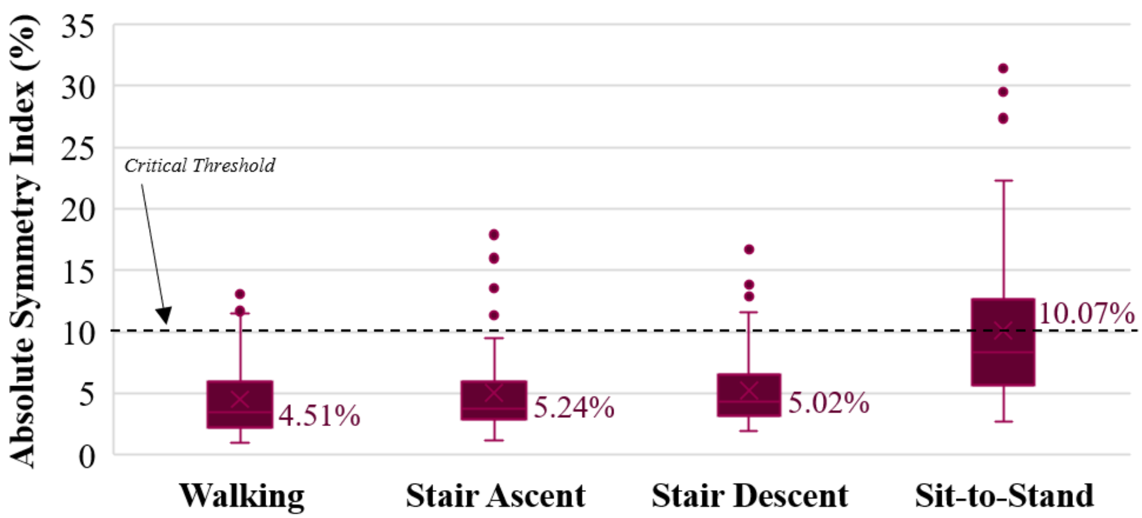

Figure 13: The Absolute Symmetry of Peak Impact Force

Tukey's post-hoc testing indicated that there were significant differences between tasks. Cohen's *d* effect sizes were used to understand the magnitude of the differences. For this test, $d > 0.8$ indicates an effect size that is clinically meaningful while $d < 0.2$ is a low effect size.[78] The effect sizes between each task are presented below in Table 3, where only the differences with the sit-to-stand task are clinically meaningful ($d < 0.8$). While there was a medium effect size reported between stair descent and walking, the difference is not clinically meaningful. Thus, there is not a meaningful difference between walking, stair ascent and stair descent ($d > 0.8$).

Table 3: Effect Sizes of Peak Impact Force Symmetry

Task Interactions		Cohen's d	P-value of Cohen's d
Sit-to-Stand	Walking	1.442	<0.001*
Sit-to-Stand	Stair Ascent	1.269	<0.001*
Sit-to-Stand	Stair Descent	1.053	<0.001*
Stair Descent	Walking	0.390	0.021*
Stair Descent	Stair Ascent	0.217	0.197
Stair Ascent	Walking	0.173	0.301

**p-value < 0.05*

Then the chi squares goodness of fit test was used to evaluate the current threshold for a healthy level of symmetry across the four daily functional tasks. For each participant, the reported ASI value for peak impact force "passed" if the value was below 10% and "failed" if the value was greater than 10%.[7,13,14] The frequency of success for the 10% threshold for each task is shown in Figure 14.

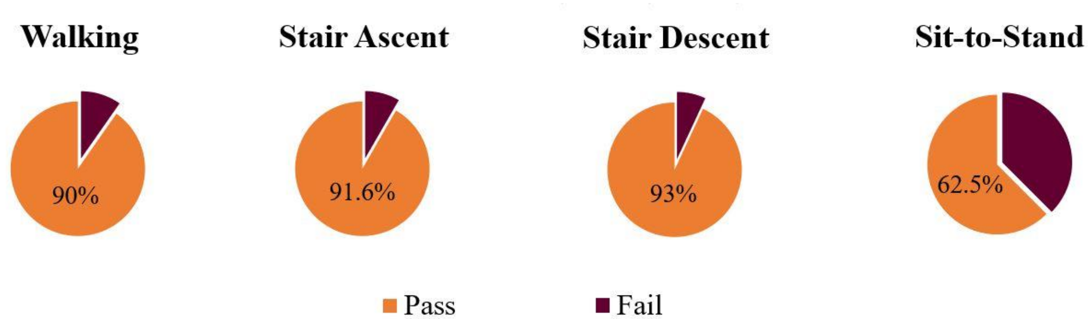

Figure 14: PIF Symmetry Threshold Comparison Between Tasks

The frequency of success for each task (W, SA, SD, and S2S) was used to calculate the chi squared value. Using a level of significance of $\alpha = 0.05$ and 3 degrees of freedom, the chi squared critical value from the chi square distribution table is 7.81.

The chi squared calculated value, $X^2 = 8.29$, is greater than the chi squared critical value 7.81 ($p=0.040$). Therefore, we reject the null hypothesis meaning that the 10% threshold of "healthy asymmetry" does not represent 95% of the population across the four daily functional tasks. However, since there was a significant difference detected between the sit-to-stand task and the other three tasks, the chi squared goodness of fit test was run again between the level walking, stair ascent and stair descent task. The level of significance was set to $\alpha = 0.05$ for 2 degrees of freedom, the chi squared critical value from the chi squared distribution table was 5.99. The chi squared calculated value, $X^2 = 0.281$, which was less than the chi squared critical value 7.81 ($p=0.869$). Therefore, we fail to reject the null hypothesis, meaning that the 10% guideline of acceptable between-limb asymmetry does accurately represent 95% of the population across these three daily functional tasks.

Average Loading Rate Symmetry

For the Average Loading Rate Absolute Symmetry Index (ALR ASI), there was not a sex by task interaction ($p = 0.448$) or main effect for sex ($p=0.213$) found. There was a significant main effect for movement task ($p < 0.001$). The distribution of average loading rate for each task are presented below in a Box and Whisker plot (Figure 15). The means are also reported next to their respective task.

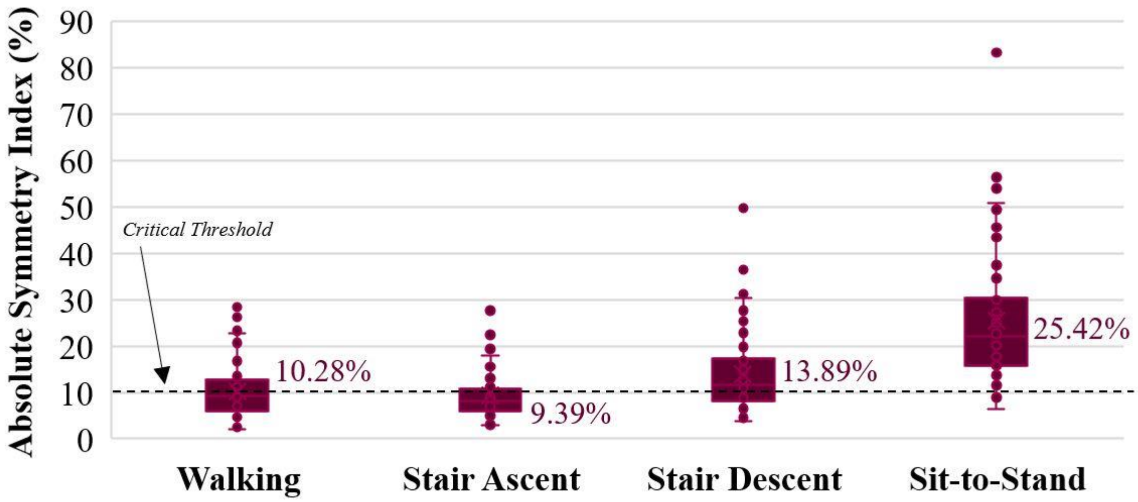

Figure 15: Sex Specific Absolute Symmetry of Average Load Rate

Since Tukey's post-hoc testing indicated that there were significant differences between tasks, the Cohen's *d* effect sizes were calculated. The value of *d* indicates the size of the standard deviation that the average ALR ASI for a participant in a single task is above the average ALR ASI for a participant in another task. When $d > 0.8$ the effect size is clinically meaningful.[78] The effect sizes between each task are presented below in Table 4Table 3, where only the difference involving the sit-to-stand task are clinically meaningful ($d < 0.8$). While there was a medium effect size reported between stair descent and walking, effect sizes of $d < 0.8$ are statistically significant, but not clinically meaningful. Thus, there is not a meaningful difference between walking, stair ascent and stair descent ($d > 0.8$).

Table 4: Effect Sizes of Average Loading Rate Symmetry

Task Interactions		Cohen's d	P-value
Sit-to-Stand	Walking	1.949	<0.001*
Sit-to-Stand	Stair Ascent	1.743	<0.001*
Sit-to-Stand	Stair Descent	1.159	<0.001*
Stair Descent	Walking	0.790	<0.001*
Stair Descent	Stair Ascent	0.585	<0.001*
Stair Ascent	Walking	0.206	0.220

**p-value < 0.05*

A chi squared goodness of fit test was used to evaluate the current threshold for a healthy level of symmetry across the four daily functional tasks. A guideline of between-limb symmetry from the literature reported that a normal level of symmetry of 10%.[7,13,14] Therefore, using the same process as described previously, the reported ASI value for average loading rate "passed" if the ALR ASI value was below the accepted normal asymmetry threshold and "failed" if the value was greater. The frequency of success for the asymmetry threshold across each task is shown in Figure 16.

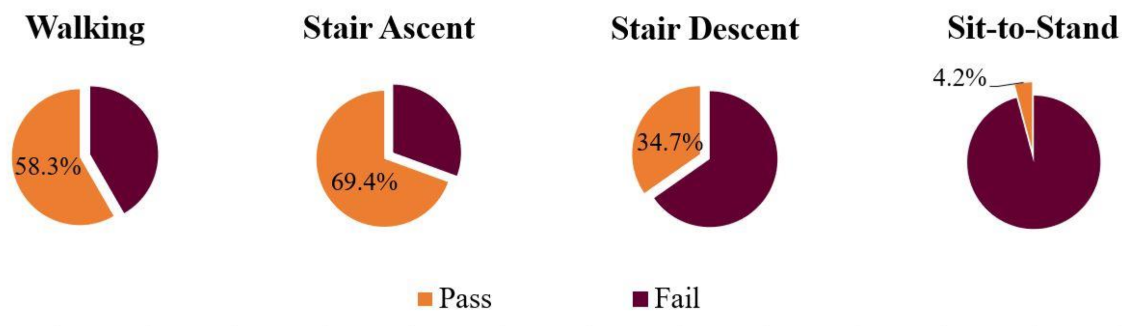

Figure 16: ALR Symmetry Threshold Comparison Between Tasks

The frequency of success for each task (W, SA, SD, and S2S) was used to calculate the chi squared value for each sex. Again, using a level of significance of $\alpha = 0.05$ and 3 degrees of freedom, the chi squared critical value from the chi square distribution table is 7.81.

The chi squared calculated value, $X^2 = 105.21$, which was greater than the chi squared critical value 7.81 ($p<0.001$). These results indicate that the null hypothesis is rejected, meaning that the 10% threshold of "healthy asymmetry" does not represent 95% of the population across the four daily functional tasks when assessing the average loading rate.

Again, a significant difference was observed between the sit-to-stand task and the other three tasks in both sexes. So, the chi squared goodness of fit test was run again between the level walking, stair ascent and stair descent tasks. The level of significance was set to $\alpha = 0.05$ for 2 degrees of freedom, the chi squared critical value from the chi squared distribution table was 5.99. The chi squared calculated value, $X^2 = 42.68$, was greater than the chi squared critical value 5.99 ($p<0.001$). Given these results, again, the null hypothesis is rejected, meaning that the 10% threshold of "healthy asymmetry" does not accurately represent 95% of the population across these daily functional tasks.

Discussion

The goal of this study was to determine differences in load symmetry during a series of activities of simulated daily living (level walking, stair ascent, stair descent, and sit-to-stand) in healthy younger adults. The first hypothesis was that load symmetry would not differ between these four tasks for an individual participant using a level of significance of $\alpha = 0.05$. For the Peak Impact Force Absolute Symmetry Index (PIF ASI), the interaction of task and sex and the between sex difference were not significant. There was a significant difference between tasks, so the null hypothesis that load symmetry does differ between tasks was rejected. However, post hoc testing showed that significant differences were only detected between the sit-to-stand tasks and the other tasks. This difference is consistent with findings published in Bishop et al.[86] that assessed symmetry in unilateral and bilateral tests. From their findings, the authors suggest that bilateral tests require a different equation to measure symmetry. This supports the loading symmetry differences observed in our study between the sit-to-stand task and the other gait related tasks assessed as part of this study. In relation to limb loading, unilateral refers to when only one limb is working at a time, while bilateral means both limbs are working simultaneously. Level walking, stair ascent and stair descent were not significantly different in loading symmetry because these tasks require both a unilateral and bilateral component while the sit-to-stand task is a bilateral loading task. Future work could expand on Bishop et al.'s work to quantify a healthy threshold of symmetry in other bilateral tests.

For the Average Loading Rate Absolute Symmetry Index (ALR ASI), there was a significant difference observed between tasks, but not in either the interaction of task and sex or between sexes. From these findings, we rejected the null hypothesis meaning the average loading rate symmetry does differ between tasks. However, post-hoc testing revealed that the ALR ASI during walking, stair ascent and stair descent were statistically different but not clinically meaningful. While there is a lack of studies that assess average loading rate symmetry in a healthy population during bilateral tasks, there are studies that have reported no significant differences in the loading rate between limbs during walking in a healthy population during gait.[5,9]

The second hypothesis was that load symmetry (peak force and loading rate) would not exceed the healthy threshold of asymmetry for any daily functional task in more than 95% of the sample. The current acceptable threshold of symmetry was developed for a clinical population in the context of recovery, with this value being set at 10% when taking the ratio of the injured limb to the non-injured limb.[13,14] This study found that a 10% threshold may not be acceptable for a peak force symmetry index across all four tasks, but is acceptable when describing level walking (PIF ASI = 4.51%), stair ascent (PIF ASI = 5.25%) and stair descent (PIF ASI = 5.02%). The symmetry values in a healthy population are consistent with findings in gait in able-bodied participants from Herzog et al.[23] that reported an average vertical force symmetry index to be 1.7% ± 6.3% and from Nigg et al.[87] that reported an average vertical GRF symmetry index to be 3.5% ± 1.7%. Although the average PIF ASI values in walking, stair ascent and stair descent are less than 10%, the upper limit of the standard deviation is around 10%, thus the findings in this study support the 10% value as an acceptable benchmark for healthy asymmetry.[7,13,14]

Similarly, for ALR, it was observed that the healthy threshold of asymmetry is not acceptable across all four tasks, describing level walking, stair ascent and stair descent since ($p<0.001$). The average loading rate is a good load metric to examine differences in motor skill and discrepancies between tasks, but the results from this study suggest that the 10% threshold is not a valuable for ALR during these movement tasks. The 10% threshold of asymmetry is used by clinicians to determine when it is safe for an athlete to return to play following an injury and to assess changes in locomotion in various clinical populations.[7,13,14] Although, the average ALR ASI value for stair ascent was under the 10% threshold, the deviation for all four tasks exceeded the 10% benchmark. Thus, it is important to understand that, when the 10% clinical threshold was set it was not based on the ALR which is not an outcome that has been traditionally used to assess rehabilitation[88] In addition, if the ALR is potentially used to assess rehabilitation, a different threshold should be defined.

A limitation of this study was that only one bilateral movement considered to be a daily functional task was observed. Another limitation was that the expected value for the chi squared analysis given that no literature has defined what makes a threshold acceptable for a population or how best to set this threshold. Therefore, the level of statistical significance was selected to be 0.05 and an expected value of 95% was used for the evaluation of the appropriateness of the 10% threshold.

Ch. 4 Conclusions

The assessment of an individual's load symmetry across varying tasks will provided an improved understanding of task specific symmetry and variability in healthy younger adults. The first goal of this work was to characterize movement variability between tasks with an in-shoe force measurement device by assessing between trial variability during activities of daily living (level walking gait, stair ascent, stair descent, sit-to-stand) in a healthy adult population. The Coefficient of Variation was calculated between trials for Peak Impact Force and Average Loading Rate using data from the single sensor loadsol®. Only the data from the right limb was used for the analysis since it represents the dominant limb for the majority of individuals. For both PIF and ALR, there was no sex by task interaction or a statistical difference between sex observed. Thus, this study showed that variability exists between each of the different tasks. For PIF, differences were significant between each task, while in ALR significant differences were only seen between tasks when compared to the sit-to-stand.

This difference was a result of the type of movement, since level walking, stair ascent and descent are all repetitive movements, while the sit-to-stand is not. The sit-to-stand task potentially utilizes a different control strategy than tasks such as walking and stair climbing. Also, for both measures the ranking of variability between the tasks was the consistent with the sit-to-stand task having the largest mean CV indicating that this task has the largest difference in the way the task is being completed range of movement. Walking resulted in the smallest mean CV due to the need for consistent joint coordination to ensure efficient locomotion.

Although variability is commonly associated with an increase in error and decrease in accuracy, variability between tasks represents how the motor skills and joint coordination change during different tasks. The assessment of variability could provide a better understanding of task complexity and could expand the understanding of the potential use of these measures to improve rehabilitation techniques, recovery benchmarks and injury prevention techniques.

The second goal of this work was to determine differences in load symmetry between sexes during a series of daily functional tasks (stair ascent and descent, level walking and sit-to-stand) in healthy younger adults. When assessing peak impact force and average loading rate, the symmetry of the sit-to-stand task was significantly different from the other tasks, which is believed to be associated with the bilaterally of the sit-to-stand task. These results provide a better understanding of the utility of the 10% benchmark that is traditionally used for the determination of healthy asymmetry. While the threshold of 10% is reliable in for peak impact force when describing healthy symmetry in walking, stair ascent and stair descent for certain measures, the significant difference observed between these tasks and the sit-to-stand task suggests the need to redefine a healthy benchmark of symmetry during bilateral tasks such as squatting or a counter movement jump. This study also demonstrated that this benchmark is only applicable for certain outcome measures.

A shortcoming of this study is that load symmetry was evaluated using parameters linked to the ground reaction force. Polk et al. concluded that ground reaction forces are largely symmetrical, and that asymmetries are more commonly identified in mediolateral force and impulse parameters.[89] Additional studies could explore changes in the load symmetry threshold during other tasks that are sport specific such as squatting, running, hopping, and jumping to inform future injury prevention and rehabilitation programs. Another limitation of this study is that all participants were young adults. While this was part of the definition for evaluating a healthy level of symmetry, the threshold is also used as a standard to assess age-related diseases. Since an increase in muscle fatigue is observed in a healthy elderly population[90], future work could explore age related differences in movement variability and symmetry.

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