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Combined effects of leg length discrepancy and the addition of distal mass on gait asymmetry

Haris Muratagic, Tyagi Ramakrishnan, Kyle B. Reed*

University of South Florida, United States

A R T I C L E I N F O

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A B S T R A C T

Asymmetries in gait often arise due to some form of physical impairment. For example, a leg length discrepancy (LLD) or the change of limb mass can result in asymmetric gait patterns. Although adding mass and LLD have been studied separately, this research studies how gait patterns change as a result of asymmetrically altering both leg length and mass at a leg's distal end. Spatio-temporal and kinetic gait measures are used to study the combined asymmetric effects of placing LLD and mass on the opposite and same side. There were statistically significant differences for the amount of mass and leg length added for all five parameters. Contrary to our hypothesis, there was no significant interaction between the amount of mass and leg length added. There were cases in all perturbations where a combination of mass and LLD make a gait parameter more symmetric than a single effect. These cases exhibit the potential for configurations with lower overall asymmetries even though each parameter has a slight asymmetry as opposed to driving one parameter to symmetry and other parameters to a larger asymmetry.

1. Introduction

Walking requires precise interlimb coordination, and impairments, such as stroke or amputation, cause the person's body to be inherently asymmetric. Able-body subjects often express up to 4–6% gait asymmetry in kinetic and spatio-temporal parameters [1,2]. A study by Seeley et al. [3] showed that propulsive force asymmetry increased during fast walking in able-body subjects, while a similar study by Goble et al. [4] showed vertical force asymmetry at slow speeds. From a dynamics perspective, two physically different systems (i.e., legs) can only have the same motion if the forces controlling them or the forces resulting from the movement are different [5]. When step length is forced to be symmetric in a person with an asymmetric impairment, asymmetric forces are generated [6]. This force asymmetry results in improper weight distribution between the limbs [2,7,8]. Thus, restoring kinematic symmetry will be at the expense of dynamic symmetry, or vice versa. In other words, an asymmetric person likely cannot walk completely symmetrically and it is not clear that this should be the goal [9]. This paper examines the effects on gait measures from changing two different physical parameters (leg length and leg mass), which will both be discussed below.

Weighted walking is commonly studied in mobility rehabilitation [10], strength training [11], and assessing aerobic ability [12]. When mass is added to the limbs, especially at the distal end, it disrupts the spatiotemporal symmetry and causes metabolic strain [13]. One study found that subjects changed their walking posture and moved their arms to maintain balance when mass was added to the distal end of their leg [14]. Skinner et al. [15] found that oxygen consumption increased by 7.4% when testing subjects with asymmetric compared to symmetric mass conditions. Asymmetrically applied weights changed the stance phase of the weighted limb, while symmetrically applied weights showed little change. Stroke patients wearing symmetrically weighted garments showed no significant change to either balance or gait asymmetry [16]. However, adding weight to the non-paretic limb of stroke patients showed significant changes in velocity, cadence, step length, and weight bearing on the paretic limb [17]. Ataxia patients wearing a 2 lb. mass on their chests showed improvement of stability and efficiency during gait [18]. Similarly, limb mass is an important aspect of prosthetic design since it leads to a myriad of problems in ambulatory gait [19]. The gait of prosthetic users becomes more asymmetric as the mass of the prosthesis approaches the mass of the normal limb [20]. Asymmetry in lower limbs is referred to as leg length discrepancy (LLD), and it affects between 40% [21] to 70% [22] of the population. LLD typically refers to the entire lower limb, but we are only able to systematically change the shank length in the study presented here. Although the majority of people with LLD possess a small difference (< 2 cm), one in a 1000 people have an LLD greater than 2 cm [23,24]. Although only about 0.001% of the population who have

* Corresponding author at: University of South Florida, 4202 E. Fowler Ave., ENB118, Tampa, FL 33620, United States.
E-mail addresses: Haris.muratagic@sofwerx.org (H. Muratagic), tyagi@mail.usf.edu (T. Ramakrishnan), kylereed@usf.edu (K.B. Reed).

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LLD use some form of corrective gear [25], large LLDs without corrective gear can cause physical problems, such as gait asymmetry [23]. Other problems include abnormal foot loading patterns and the corresponding rise of joint torques/moments [26] and the changed forces can result in back pain, which are often reported in the general and prosthetic populations [27]. Increases in LLD showed higher gait asymmetry in able-bodied subjects, both children [28] and adults [29]. Propulsive forces during toe-off and braking forces during heel strike are highly asymmetric with a LLD greater than 2 cm. People with LLD also exert more energy during gait, which leads to higher physical strain [30].

Although LLD and mass effects have been studied separately (as described above), they have not been jointly examined. Further, most prior studies analyzed either spatio-temporal *or* kinetic parameters. This study is focused on understanding the effects of changes in both mass and length as well as understanding the interactions between spatio-temporal parameters (e.g., step length and time) and kinetic parameters (e.g., vertical, propulsive, and braking forces). We chose these parameters because they are widely used in the literature and there is evidence that the asymmetries of these parameters influence each other [7,5]. Therefore, this analysis of artificially induced morphological changes in leg mass and length examines the relationships between their interactions.

The goal of this study is to understand how multiple physical changes affect a person's gait. In many of the above studies, the focus of the analysis was on a few gait parameters, so the effects on many other related parameters is not known. For example, if a rehabilitation method makes the step length symmetric, what does this do to other parameters? And, is there a balance such that all of the gait parameters can be close to symmetric even of none are perfectly symmetric?

2. Methods

2.1. Equipment

The experiments were performed on the Computer Assisted Rehabilitation ENvironment (CAREN) system. This system includes a split belt treadmill, two individual force plates, and a six degree of freedom platform. The CAREN system includes a 10 Vicon® Bonita B10 infrared camera motion tracking system that records at 120 Hz. The kinematic data was recorded using 8 infrared markers (14 mm diameter), placed at the hips, knees, toes, and heels. The kinetic data was collected using Bertec force plates mounted under the treadmill. The preferred baseline walking velocity used for all trials was calculated based on a standard 10 m walk test.

2.2. Physical parameters

We applied perturbations consisting of either a leg length change, mass change, or a combination of both. Leg length changes were either small (2.7 cm) or large (5.2 cm), Fig. 1(a). Small LLD reflects a height difference slightly larger than 2 cm LLD [30,23], which is considered detrimental and the large LLD represents an extreme condition. To change the leg mass, a weighted ankle strap was attached. The added weights were either small (2.3 kg) or large (4.6 kg), Fig. 1(a). These masses were chosen based on a preliminary study that compared the changes in human gait under a perturbation to that of a passive dynamic walker under the same mass change [31]. We used a linear increase (x and $2x$) in each case for simplicity since we wanted to represent none, small, and large conditions.

Fig. 1(b and c) shows the physical perturbations consisting of added leg length and/or mass for a right-limb dominant subject; left-limb dominant subjects had all perturbation sides flipped. Leg length was added to the left foot of the participants. Limb dominance was determined by the ball kick test, which assumes the dominant leg is used to kick a ball [32]. Disrupting the non-dominant side by altering leg length and mass is expected to cause the person to exhibit a more asymmetric gait pattern.

2.3. Participants

All experiments were conducted after informed consent using procedures approved by the University of South Florida's Institutional Review Board. There were twenty subjects (13 male, 7 female) that participated in this study, all with limited to no exposure with physically induced asymmetric walking. The age of the participants ranged from 18 to 30 years, with no physical impairments, past lower limb injuries, or large LLD > 2 cm [30]. The average height, leg length, weight, and walking speed of the participants was 1.785 m, 0.981 m, 82.8 kg, and 1.22 m/s, respectively. Leg length was measured from the greater trochanter to the ground. This method is not as accurate as an X-ray or MRI imaging results. However, none of the subjects were clinically diagnosed with LLD.

2.4. Procedure

The experiment was conducted in two phases: phase one had perturbation combinations on opposite sides while phase two had perturbation combinations on the same side. Phase one included 10 subjects (8 male and 2 female) where nine of the ten participants in the study were right leg dominant. The data of the left foot dominant subject was mirrored to be included in the analysis. The right foot was always used for the applied weight in this phase, LLD was always applied to the left foot, and the combinations were on opposite sides, Fig. 1(b). The second phase consisted of 10 subjects (5 male, 5 female), all right dominant. All perturbations were applied on their left leg, Fig. 1(c). All perturbations were applied in a random order for both groups. Each subject walked with each perturbation for two minutes with breaks in between as needed.

2.5. Analysis and statistics

The altered gait patterns are measured using the percentage of asymmetry between each leg, calculated using Eq. (1), for step length, step time, peak vertical force, propulsion force, and braking force. Step length was measured from heel strike of left foot to heel strike of right foot or vice versa. Step time was the calculated using the differences in time stamps between heel strikes. These biomechanical parameters were chosen because they impact a person's gait pattern and are generally shown to be asymmetric due to physical and neurological impairments [20,17].

$$\text{Percentage of Asymmetry} = \frac{\text{right} - \text{left}}{1/2^{*}(\text{right} + \text{left})} \tag{1}$$

The gait data is normalized to the baseline/unaltered walking pattern of the subjects such that baseline/unaltered gait is always at zero asymmetry (i.e., 0 on y-axis with no added length of mass). The means of step length (−2.9%), step time (−0.39%), vertical force (−1.6%), propulsive force (−4.3%), and braking force (−3.5%) were subtracted from all of the respective graphs to normalize the plots. This normalization was done to ensure continuity between the length and mass perturbations being applied to the same and opposite limbs to focus on the change in gait pattern.

SPSS software was used to perform a multivariate ANOVA. The dependent variables were each of the five gait parameter asymmetries and the independent variables were LLD and mass with interaction effects. Fig. 2(a–e) shows each of the five parameters as a function of mass and leg length with the 95% confidence intervals determined using a post-hoc test with Bonferroni corrections.

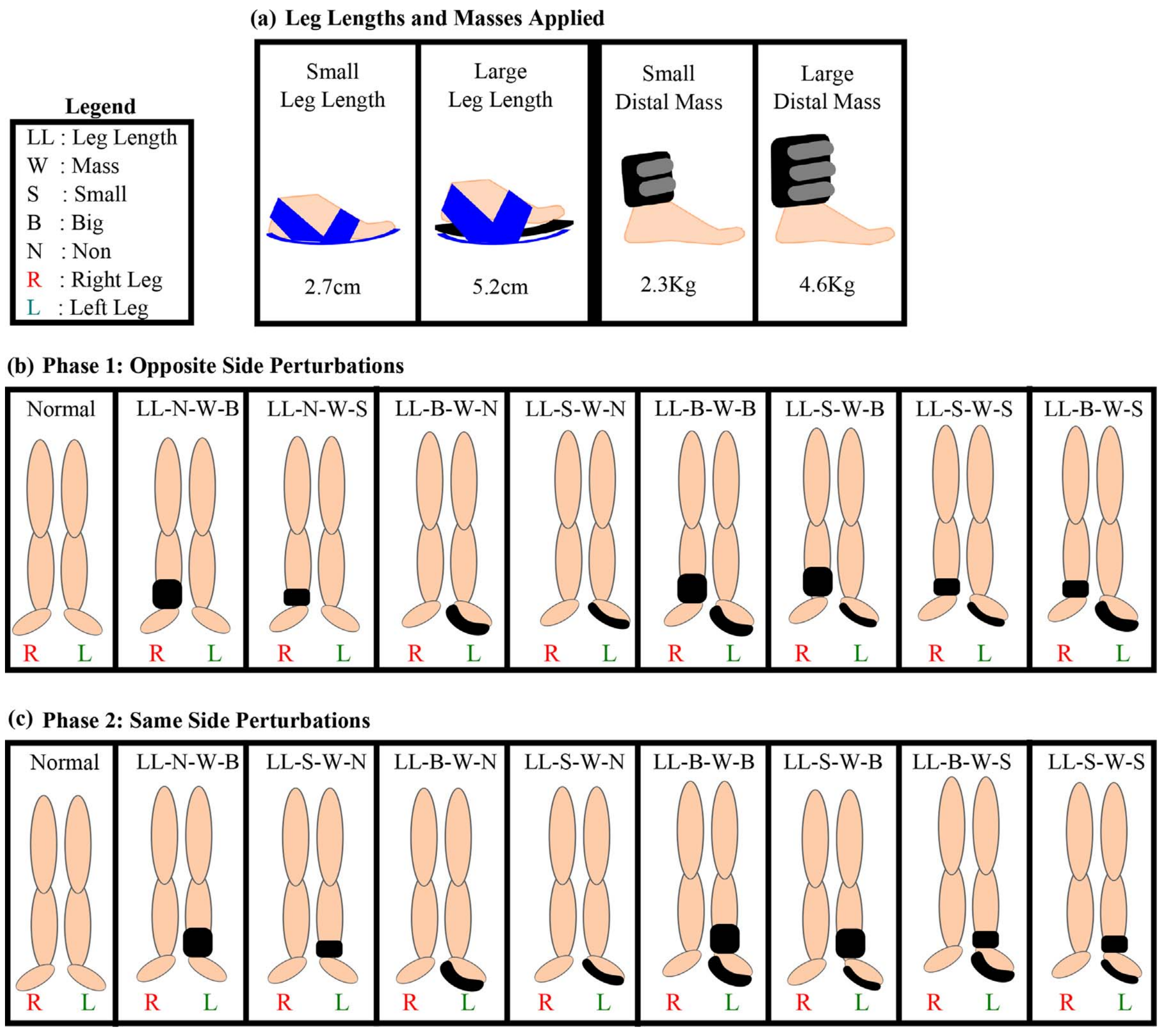


Fig. 1. The different combinations of perturbations tested in this study.

3. Results

The *y*-axis on Fig. 2(a–e) reports the percent asymmetry of the five measures where the positive and negative direction signifies larger right and left asymmetries, respectively. The *x*-axis represents the mass configuration with the right side showing mass added to the same limb while the left displays the mass on the opposite limb as the added leg length. The three lines represent the different leg lengths. The statistically significant differences for the five different mass configurations are displayed as bars on top of each graph, and the statistically significant differences for the three leg lengths are represented by bars next to the legend.

Step length exhibits an opposite response compared to the other gait parameters. With no added mass, an increase of leg length causes a left asymmetry in step length, but a right asymmetry in the other parameters. Similarly, the effect of adding mass is reversed for step length compared to the other parameters; the LL lines generally slope up to the right for step length, but down to the right for the other four parameters.

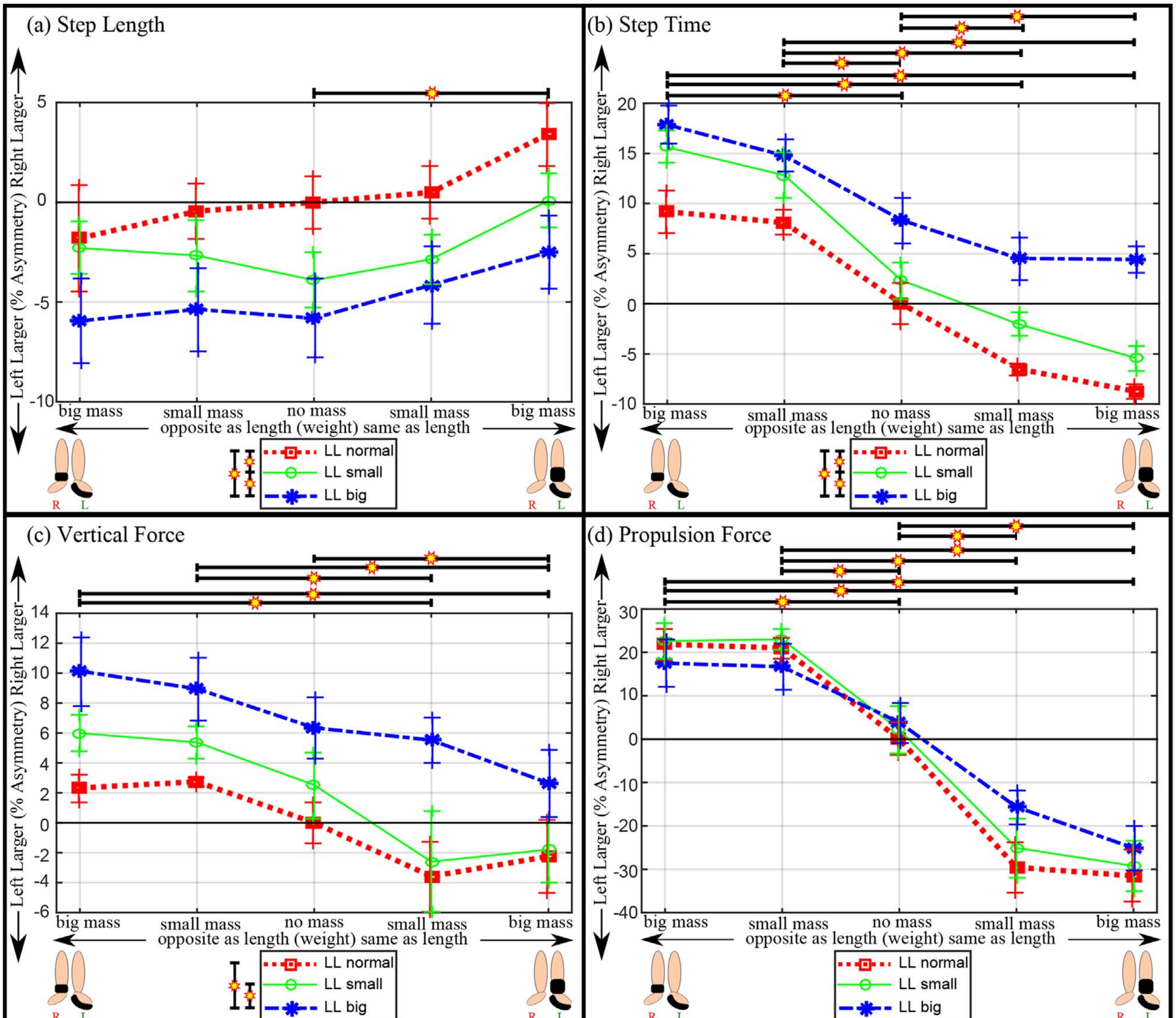
Adding mass in combination with leg length shows two force trends. In the opposite side condition, the forces became more asymmetric towards the shorter right limb and the step time asymmetry shifts toward the shorter limb. Adding mass in the same side condition did the exact opposite with the exception of vertical force asymmetries due to large leg length. Adding mass on the same side shifts the direction towards the longer limb, except in the case of big leg length. The step length does the reverse of step time. The results also found adding mass to any leg increases the step time in the direction of that limb.

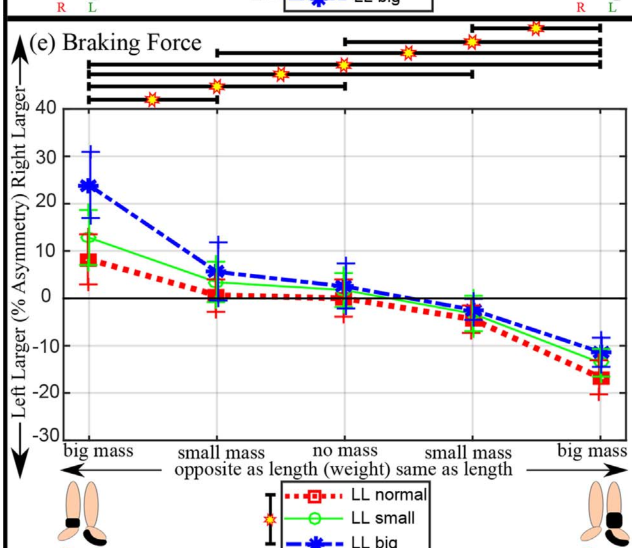
There is a statistically significant difference between no mass and big mass in all measures, with the exception of step length and vertical force on the opposite condition. Step time and propulsion forces have the same pattern for significances. Braking forces show significance between big and small masses in both opposite and same side conditions.

There is statistical significance between all three leg length conditions for step length and time. There is no statistical significance between all conditions for propulsive forces. Vertical forces show statistical significance for the normal and large leg length condition and for small and big leg lengths. Braking forces only display significance between normal and large leg length.

4. Discussion

An important finding from this experiment is that there is no significant interaction effect between the addition of mass and leg length for all gait parameter asymmetries, Fig. 2(f). We initially expected interaction between these mass and leg length alterations because they both affect the gait patterns, but in different ways. There was significance for all parameters for mass effect and leg length with the exception of propulsion forces. These results imply that the addition of mass will have the same gait change regardless of whether there is a LLD or not and similarly for the addition of a LLD with an added mass





(f) Summary of Statistics. Bold Implies Statistically Significant.

Measure	Mass Effect	Height Effect	Interaction Effect
Step Time	**p < 0.0001** F(4,165) = 87.5	**p < 0.0001** F(2,165) = 56.0	p = 0.08 F(8,165) = 1.8
Step Length	**p < 0.05** F(4,165) = 2.9	**p < 0.0001** F(2,165) = 15.3	p = 0.97 F(8,165) = 0.29
Vertical Force	**p < 0.0001** F(4,165) = 9.6	**p < 0.0001** F(2,165) = 22.6	p = 0.84 F(8,165) = 0.53
Propulsion Force	**p < 0.0001** F(4,165) = 137.0	p = 0.26 F(2,165) = 1.35	p = 0.18 F(8,165) = 1.44
Braking Force	**p < 0.0001** F(4,165) = 137.0	**p < 0.05** F(2,165) = 4.1	p = 0.73 F(8,165) = 0.66

Fig. 2. Normalized plots and statistics summary of (a) step length, (b) step time, (c) vertical forces, (d) propulsion forces, and (e) braking forces for the different leg lengths and distal masses. Each plot shows the 95% confidence intervals and the post-hoc results for added mass are shown on top of the graph and added length to the side of the legend.

on one side. Interaction effects may be found with larger perturbations, but the magnitudes used here span the range of asymmetries typically seen [21,22,33,34]. The results of this study indicate that differences in asymmetric gait patterns can drive some gait parameters to symmetry while causing the inverse effect on the rest of the parameters. This shows that a balance of multiple gait parameter asymmetries might be clinically beneficial. Designing rehabilitation protocols with this in mind will help improve the quality of gait patterns post training.

The results show there are configurations where one parameter is symmetric in an asymmetric person. For example, step length is close to symmetry (0.075%) when a big mass and small leg length were added to the same leg, but this resulted in a highly asymmetric step time (−5.4%), vertical (−1.78%), propulsion (−29.24%), and braking forces (−13.61%). This is consistent to other studies exploring LLD and addition of mass, which found significant changes in parameters between leg lengths and kinetics associated with these configurations [9,35]. The same side conditions tend to have the symmetric parameters more so than the opposite side conditions.

With no mass added, the forces show an approximately linear increase in their asymmetry with leg length change. In the no-mass condition, the unaltered leg compensates by generating large forces to maintain the gait, Fig. 2(c–e). The increase in forces has been observed in prior studies with simulated LLD [29,24]. However, subjects with a natural LLD tend to exhibit more force on their longer limb [23,36]. We believe this difference in behavior can be attributed to the adaptation period of simulated and natural LLD subject populations.

Subjects with LLD and amputees with shorter prosthetics have smaller step times on their shorter limbs compared to longer limbs [23,27]. This is not consistent with our findings. The step times show a linear increase with change in leg length towards the shorter limb. However, the same studies also found subjects with LLD take smaller steps with their shorter limbs. This does correlate with our findings. The general behavior of the subjects with simulated leg length is to spend more time on their unaltered limb and use that leverage to swing their altered limb to maintain the stability required for their gait on a constant velocity treadmill. They also spend less time on their altered limb and quickly switch to their unaltered limb.

Compensatory motions influence gait asymmetries with mass and leg length alterations. This is clinically relevant because patients with impairments tend to develop compensatory movements. This results in long-term effects such as chronic back pains in amputees with asymmetric prosthetic lengths [27]. Adding mass to prosthetics increase step length and swing time asymmetry of the prosthetic compared to the intact limb [20]. Amputees swing their prosthetics out and hence have larger step length and swing time. Able body subjects tend to take smaller steps and spend more time on the altered limb to conserve energy while taking longer steps with the unaltered limb. Long term effects of these gait alterations may lead to completely different gait mechanics than reported in the results. This is because subjects tend to use different compensation strategies over the long term compared to the short-term tested in this research.

5. Conclusions

The results of adding both leg length and mass demonstrate that driving one of the gait parameters to symmetry will cause the other gait parameters to become more asymmetric. There are instances where a gait parameter can be symmetric when walking with asymmetric height and weight, but we did not find a configuration where several of the measured gait parameters became more symmetric in an asymmetric person. Although there is a statistically significant effect between the addition of mass and leg length, there was not a significant interaction between the mass and leg length change. The kinetic and temporal parameters exhibit higher asymmetry on the shorter limb for leg length condition while the spatial parameter shows that asymmetry moves towards the altered leg. Similarly, the addition of mass shifts the trend towards the affected leg in the temporal and kinetic parameters but they affect the opposite leg spatially. Finally, although there was no statistically significant interaction effect, this study has shown the behavior of multiple gait parameters. This gives an overall perspective of the effects of LLD and addition of distal mass in multiple perturbations.

Conflict of interest

The authors do not have any conflict of interest for the research presented in this article.

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