International Journal of Current Advanced Research
ISSN: O: 2319-6475, ISSN: P: 2319-6505, Impact Factor: SJIF: 5.995
Available Online at www.journalijcar.org
Volume 6; Issue 10; October 2017; Page No. 6896-6903
DOI: http://dx.doi.org/10.24327/ijcar.2017.6903.1037

Research Article

EFFECT OF ASYMMETRIC KNEE HEIGHT ON GAIT ASYMMETRY FOR UNILATERAL TRANSFEMORAL AMPUTEES

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ARTICLE INFO

Article History:

Received 20th July, 2017
Received in revised form 29th August, 2017 Accepted 25th September, 2017

Key words:

Asymmetry; Amputee; Knee Height

ABSTRACT

Transfemoral prostheses have traditionally sought to emulate symmetry in their designs. Using a symmetric prosthesis for a physically asymmetric unilateral transfemoral amputee typically causes asymmetric gait patterns. This research study investigates the effects of prostheses with lower knee heights than the intact knee and a pilot study of the combined effects of adding distal mass with lower knee heights. To test the effects, one unilateral transfemoral amputee was tested with four different knee heights as well as with and without a distal mass. Further, six able-body subjects were tested while wearing prosthetic simulators with three different knee heights and no distal mass. The results showed that the amputee and able-body subjects wearing prosthetic simulators showed better overall symmetry with lower knee heights in spatiotemporal, kinematic, and kinetic parameters. Specifically, the amputee showed improved symmetry in step length and kinetics. The addition of distal mass in combination with lower knee height showed better symmetry than cases without distal mass for the amputee gait. The kinematics showed decreased hip angles in all cases. The tests with the prosthetic simulators showed decreased knee and ankle angles. This study indicates that there are potential benefits to overall gait symmetry by lowering the knee height of a unilateral transfemoral prostheses. The study also showed that changes in distal mass in combination with lower knee height can improve gait symmetry.

INTRODUCTION

Human gait is a testament to the importance of symmetry in movement. Symmetry can be found in many facets of humanity including art (Begleiter, 1984), material science (Yeung *et al*., 2015), and communication (Iachello *et al*, 2012). For gait to be perceived as normal, it is mostly symmetric in spatial, temporal, and kinematic parameters. Gait symmetry is often used to evaluate the efficacy of lower limb rehabilitation techniques. Human gait involves precise neuro-muscular coordination to bring about a cyclic pattern of motion. Able-body subjects with no physical alterations express about 4 – 6 % gait asymmetry (Herzog *et al*., 1989; Sadeghi *et al*., 2000). Transfemoral amputees have more asymmetric gait patterns compared to able-body or transtibial amputees (Highsmith *et al*., 2010).

A unilateral transfemoral amputation renders a person physically asymmetric. Most existing designs of transfemoral prostheses strive to achieve symmetrical dimensions and movement by replicating the parameters of the healthy leg as closely as possible. This forces a physically asymmetric person to have a symmetric form, with the expectation that the center of mass on above-knee amputees and found no significant increase to metabolic cost. Similarly, Mattes *et al*. (2000) altered the mass configurations on amputees to better match the moment of inertia of the healthy leg to discover the resultant gait had greater asymmetries and metabolic costs. This evidence suggests that a symmetric gait might be more closely achieved using parameters for the prosthesis that are different from the healthy leg because of the inherently asymmetric nature of using a prosthesis. Human gait has been modeled using passive dynamic walkers (PDW) (McGeer, 1990). PDWs are passive bipedal systems that contain two double pendulums that represent the legs. These bipeds exhibit human like gait walking down a slope propelled by gravity. Previous research on asymmetric PDW models showed that they can successfully simulate an asymmetric gait pattern (Handzic *et al*., 2013). Using a mass model developed by Chen (2007), Sushko *et al*. (2011) found that a symmetric step length was possible with an asymmetric mass distribution by varying the position of the knee. A system that has reduced the total mass with a symmetric step length was achieved by lowering the knee position on the passive dynamic walker. This result led to the hypothesis that a prosthesis with a lower knee height can enable transfemoral amputees and subjects with knee disarticulations to have a better overall gait pattern that is less detrimental (Sushko *et*

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al., 2012). For example, a 36.7% reduction in knee height allows for the mass of the leg to be reduced by 13.4% while maintaining a symmetric gait pattern. Both the modeling of human gait using passive dynamic walkers and double link pendulums evaluated asymmetric mass distribution by moving the position of the knee joint and were able to achieve symmetry (Handzic *et al*., 2015). Lifting the restrictions on the knee position of a prosthesis design opens a wide range of design possibilities. The knee position could be individually customized for the user creating a more personalized and cheaper prosthesis.

Symmetry is also important in the visual perception of a prosthesis. Visual perception is often evaluated using a scale of likeness of human motion and physical proportions. Low scores on this perception scale indicate that the object has an unusual or eerie feeling (Handzic and Reed, 2015). On the uncanny valley, prostheses are considered to be similar to human characteristics yet they are perceived to have a somewhat strange motion since they do not generate a perfectly human-like motion (Mori, 1970). The goal of prosthesis design is to maintain or improve likeness of the devices while improving familiarity and function. Achieving symmetry in gait kinematics is considered to help achieve these goals. Symmetry's aesthetic appeal as evident in Leonardo da Vinci's vitruvian man (Naini *et al*., 2006). A different knee height would provide a larger range of possibilities to achieve the visual benefits of kinematic synchronization (Handzic *et al*., 2015). Moving the height of one knee may allow movement symmetry, but could create an asymmetric appearance. To evaluate this height asymmetry, Handzic and Reed (2015) tested the visual perception of gaits created from different knee heights. They found that reducing the height of one knee by up to 26% was found to be perceived as minimally impaired and an above neutral perception rating. These results indicate that the position of the prosthesis is unlikely to be detrimental for small knee height asymmetries. This could allow for future optimization between the knee height and movement asymmetries such that both are slightly asymmetric, but within bounds that are minimally noticeable. Preliminary evaluation of the prosthesis with lower knee height using a prosthetic simulator revealed that a lower knee height does help in improved step length symmetry, facilitate larger steps, step time symmetry, and vertical force symmetry (Ramakrishnan, 2014). To evaluate the effects of the knee heights further, this study looks at eleven gait parameter asymmetries that includes spatiotemporal parameters such as step length and time, joint kinematics and kinetics, and the reaction forces. The overall gait pattern is evaluated by combining the eleven gait parameters to calculate the Combined Gait Asymmetry Metric (CGAM) (Ramakrishnan *et al*., 2016). CGAM is used in this study to evaluate the overall gait patterns with different knee heights. The gait parameter asymmetries along with the CGAM will be used to draw conclusions of the efficacy of gait with lower knee heights.

MATERIALS AND METHODS

CAREN

All the experiments were conducted on the Computer Assisted Rehabilitation Environment (CAREN). The CAREN is equipped with ten infrared Vicon motion capture system, split-belt treadmill, six degree of freedom motion platform, continuous force plates, and a 180° panoramic screen for immersive rehabilitation protocols. The study was conducted in two phases: phase 1 was a test case with a unilateral transfemoral amputee, and phase 2 consisted of 6 able-body subjects who walked using a prosthetic simulator on the CAREN.

Protocol and Participants

All seven subjects (one amputee and six able-bodied) agreed to participate and signed an informed consent form. The experimental procedure and consent form were approved by the University of South Florida's Institutional Review Board. All subjects were asked to walk continuously on the altered prosthesis and prosthetic simulators for at least 1 minute. Motion capture and force plate data was collected throughout the time the subjects walked on the CAREN. The lower limb motion capture data was collected using 18 markers that were distributed around the hip, knee, and ankle joints. Walking velocities for all subjects' normal walking was based on a 10 meter walk test conducted over ground. All subjects were allowed to take breaks during the trial and wore a harness throughout the trial period attached to CAREN system for their safety.

Table 1 Participant information for Transfemoral Amputee

Parameter	Values
Sex	Female
Height	163cm
Weight	132lbs
Age	37
Knee Type	Ossur Total Knee 2000 (Passive)
Foot Type	Ossur Flex Foot (Passive)
Walking Velocity	1.3m/s
Knee Height Changes	Symmetric, 3cm, 6cm, and 9cm

Transfemoral Amputee

The unilateral transfemoral amputee was a 37 year old female with related details shown in Table 1. She is a high functioning amputee and leads an active lifestyle which made her an ideal candidate for the study. The protocol was as follows: the amputee was first tested with the symmetric knee height for 2 minutes, followed by the addition of 1 kg of mass at the ankle as seen in Figure 1 (c), followed by walking with the mass for 2 minutes. After this, the knee height was set to 3 cm, 6 cm, and 9 cm in a randomized order, Figure 1. The procedure is repeated as the amputee walks with the lowered knee height for 2 minutes, then the 1 kg distal mass is attached to the current setup, and she walks with the distal mass for another 2 minutes. The subject reported discomfort with the lowest knee height as there was an increase in terminal impact at the knee which caused more asymmetric forces on the socket.

Prosthetic Simulator

The able-body subjects volunteered to be fitted with the prosthetic simulator and walk on the CAREN system. Table 2 shows the statistics for the subjects. Every subject's shank length was measured and then we evaluated the change in height. Every subject had three knee height settings determined by their shank length using a random selection algorithm. The first parameter is the side the prosthetic simulator is attached to, as seen in Figure 2 (a).

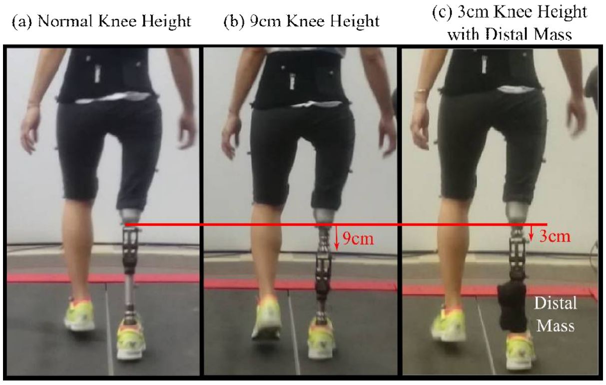

Figure 1 Tranfemoral amputee with lower knee height and in combination with distal mass

Then the knee height is decreased either 3 cm or 4 cm depending on the length of the person's shank and finally we decrease the knee height further by 6 cm or 7 cm. The knee heights that were applied to the six subjects were randomized to avoid gradual adaptation effects. Every subject trained overground to understand the dynamics of using the prosthetic simulator before being tested on the CAREN system. The able-body subjects walking with the prosthetic simulator were allowed to familiarize themselves with the simulator in order to display stable gait. They were only permitted to practice on the high knee height setting. After the training period, reflective markers are attached to the subjects and the subjects walk without the prosthetic simulator for two minutes at the velocity determined by the 10 meter walk test. After this, the subjects are fitted with the prosthetic simulator set to a random knee height and asked to walk on it at a previously determined comfortable velocity. This velocity for the prosthetic simulator was evaluated with the prosthesis at the highest knee height and it was kept consistent throughout the trial for the other knee heights. The subjects were instructed to walk for at least one minute. We found that using a prosthetic simulator was extremely tiring for all able-body subjects because of the highly asymmetric physical alterations.

Table 2 Participant information for Prosthetic Simulator

Parameter	Values
Sex	5 Male and 1 Female
Height	177 – 187cm
Weight	139 – 210 lbs
Age	19-37
Knee Type	Pediatric Knee (Passive)
Foot Type	SACH foot (Passive)
Normal Walking Velocity	1 – 1.3 m/s
Walking velocity with Prosthetic Simulator	0.6 – 1 m/s
Shank Length	51 – 57 cm
Knee Height Changes	Symmetric, 3cm, 6cm, and 9cm

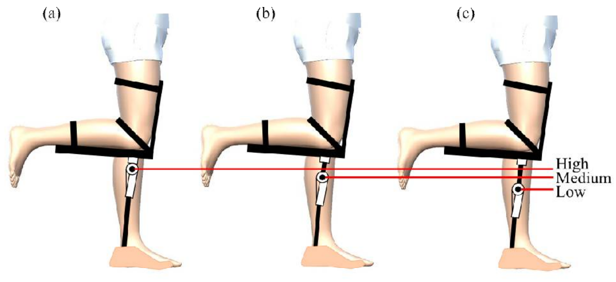

Figure 2 Prosthetic Simulator with three different knee heights

Data Analysis

The motion capture and force plate data was analyzed using Matlab scripts. The force plate data was used to calculate the ground reaction, propulsive, and braking forces. We also used the forces in conjunction with motion capture data to calculate the joint moments. The motion capture data was also used to calculate the joint kinematics and spatiotemporal parameters.The asymmetries for peak discrete values of each parameter for every step were calculated using Equation 1.

$$\text{Percentage of Asymmetry} = \frac{(Prosthetic - Intact) * 100}{0.5 * (Prosthetic + Intact)}$$

We calculated the asymmetries for all 11 gait parameters for all the subjects and their perturbations. Then used the Modified CGAM measure to calculate the overall asymmetry scores using the 11 gait parameters, as shown in Equation 2.

$$Modified\ CGAM = \sqrt{\frac{Data * Inv(\varepsilon) * Data'}{\sum(inv(\varepsilon))}}$$

Where,
Modified CGAM Distance = Weighted Distance from Ideal Symmetry
Data = Matrix with m rows (Number of Steps) and n columns (11)
ε = Covariance of the Data

The modified metric provides a weighted approach compared to the original formulation (Ramakrishnan *et al*., 2016). The combined data sets for all parameters and CGAM scores are shown in Figure 3. The joint kinematics for the amputee with and without distal mass are shown in Figure 4 and for prosthetic simulator it is shown in Figure 5.

RESULTS

The experiments were conducted to evaluate if a lower asymmetric knee height in a unilateral transfemoral amputee improve the overall symmetry of the gait. The results in Figure 3 indicate that a lowered knee height can help bring some gait parameters to symmetry, but make others more asymmetric. For example, the vertical forces of the amputee with distal mass move towards symmetry as the knee height lowers while the opposite effect takes place with knee angles, Figures 3 (D & B). Since there are many parameters, it is convenient to also look at the CGAM scores that combine all of these metrics; in essence, it determines if the gait is globally getting more symmetric even if one parameter is not. The CGAM scores for each gait pattern are shown in Figure 3 (L).

Generally, the trends show that lower knee heights do make some gait parameters more symmetric. There are exceptions where the alterations lead to higher asymmetries or show no change; for example, the moments for the amputee with distal mass and the forces for the prosthetic simulator showed no change. In the case of using prosthetic simulators, they showed distinct differences from the amputee and normal able-body gait asymmetry. We expected this but generally the behavior trends are not drastically different. This is also reflected in the CGAM scores where lowering knee height clearly improves the overall asymmetry of the amputee without the distal mass. There is an improvement in the overall asymmetry with respect to the gait with prosthetic simulators as well. However, this shows that the lowest knee height is not always the best in terms of dynamics for gait patterns.

The joint angles for the amputee subject are shown in Figure 4. The largest deviation of changes from normal patterns is seen at the hips. The subject compensates for the changes in swing time due to the smaller moment arm at the shank, which is exhibited in the form of altered hip angle patterns. The knee angles for both limbs display consistent patterns with little deviation from the baseline knee angles. The peak knee flexion angles for the 6 cm decrease and symmetric height with distal mass for the prosthesis are considerably smaller than the baseline prosthetic knee flexion. This decrease is also seen in the sound side but not to the extent of the prosthesis which is to be expected. The sound side ankle angles show higher plantar flexion in the 6 cm asymmetry while all other settings show a decrease compared to the symmetric setting. The ankle angles for the prosthetic side show higher dorsiflexion for the 3 cm asymmetry with and without distal mass compared to the symmetric knee height. The plantar flexion of the ankle decreased with the change in knee height. Hip abduction of the sound leg increases when the knee height is lowered except for the case of 6 cm asymmetry with distal mass, in which case the peak abduction angle is lower the baseline value. In the case of the prosthesis, the 3 cm and 6 cm asymmetries cause the peak abduction angle to be larger than baseline. However, with the addition of distal mass, abduction angles are lower than baseline and the 9 cm asymmetry without distal mass also shows a lower abduction angle.

Figure 5 shows the joint kinematics obtained for the prosthetic simulator trial. No distal mass was added to this set of experiments because the additional distal mass could further alter the dynamics of walking more than the alteration caused by the prosthetic simulator. Hip angles for the sound side show a decrease in peak extension, whereas the prosthetic side shows an increase in peak extension angles for the medium and low settings. There is an overall decrease in the hip and knee flexion angles with lower knee height for both limbs.

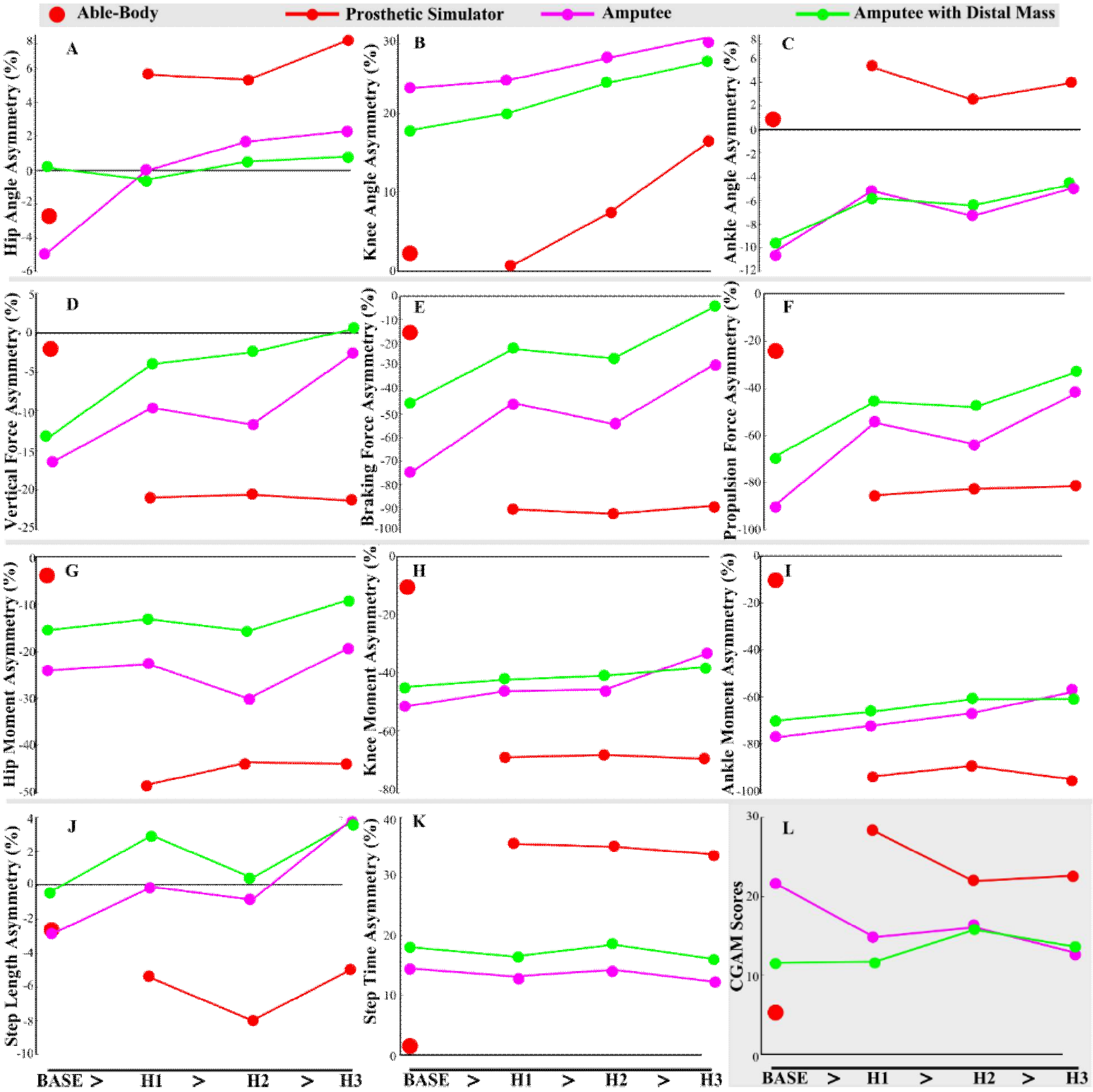

Figure 3 Consolidated results of all gait parameters and CGAM scores

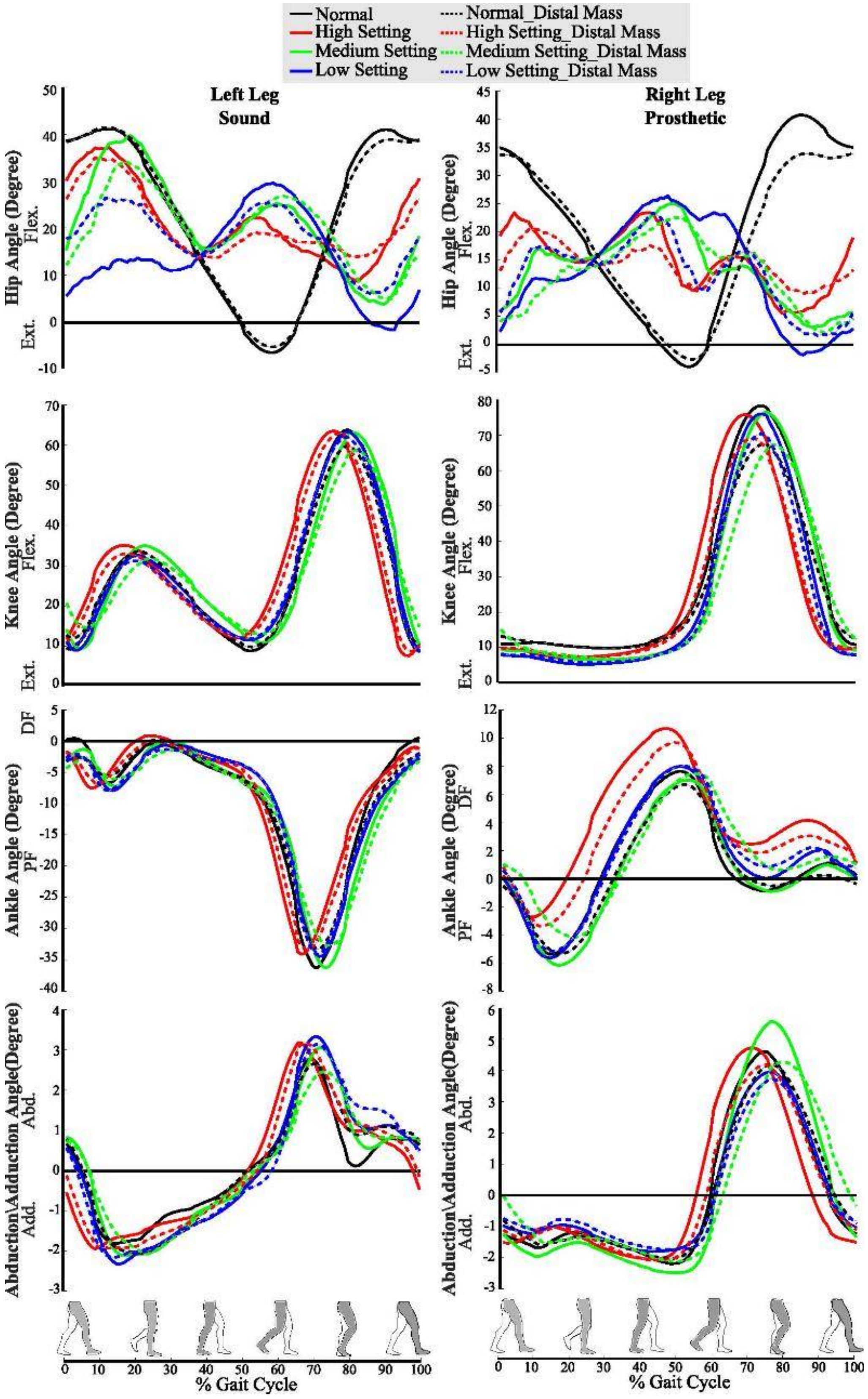

Figure 4 Joint Angles of Unilateral Transfemoral Amputee with different knee heights

Ankle angles showed larger dorsiflexion with the high setting, but the other settings resulted in no change for the sound leg. Lower knee heights showed decreases in peak plantar flexion in the sound leg. The prosthetic ankle showed lower dorsiflexion angles and no sign of plantar flexion. Hip abduction increased with the medium setting on the sound leg, no change at the high setting, but a decrease with the low knee height setting. Both abduction and adduction showed a decrease on the prosthetic side.

DISCUSSION

Lowering the knee height of a prosthesis is counterintuitive in rehabilitation where the goal is to achieve the physical ability prior to one's amputation.

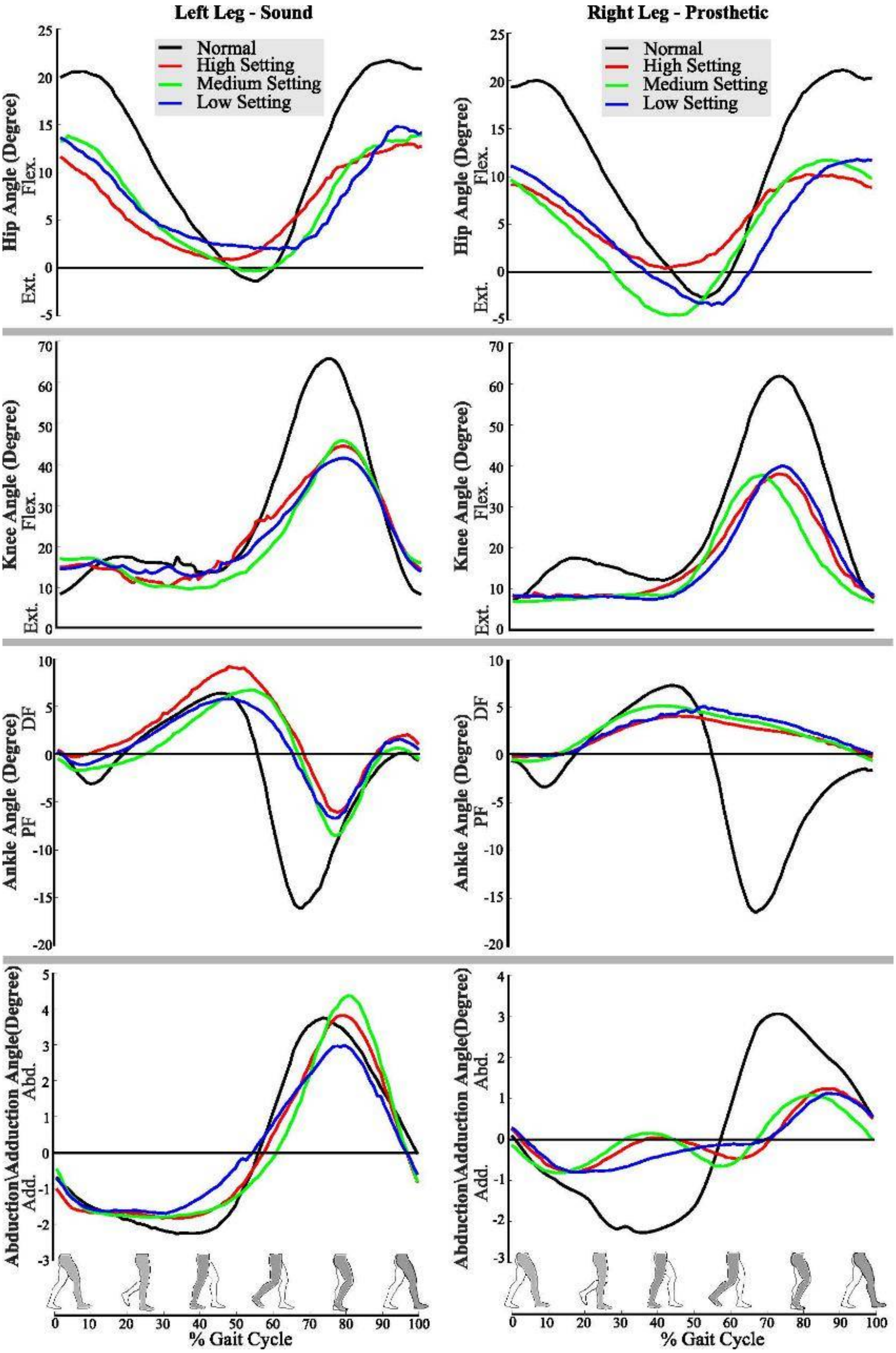

Figure 5 Joint Angles of Able Body using Prosthetic Simulator with different knee heights

In a unilateral transfemoral amputation, a person loses their knee and ankle joints that are critical to walking, which renders them physically asymmetric. Rehabilitating physical asymmetry with symmetric prosthesis often leads to spatiotemporal and kinetic asymmetries (Highsmith *et al.*, 2010; Kaufman *et al.*, 2012).

This study shows that gait asymmetry can be mitigated by asymmetric alterations such as lowering the knee height, adding distal mass, or a combination of the effects (Muratagic *et al.*, 2017).

Evaluating the different asymmetries and kinematics of the gait reveal that there are distinct differences that arise due to lowering knee height. The most important of the effects being the shorter moment arm which in-turn causes longer swing times from flexion to extension. Since the study was conducted on a treadmill at constant velocity, the step time asymmetries do not change with the different knee heights. However, we do see that the step length becomes more symmetric with the 3 cm and 6 cm change in knee heights for the amputee. The prosthetic simulator at the highest and lowest settings were more asymmetric than the medium knee height. The spatiotemporal parameters are also visual indicators and, from Figure 3 (J-K), we can see that a lowered knee height pushes the step length to be symmetric. Step time shows no change between baseline and different knee heights in both amputee and prosthetic simulator gait.

Joint moments also do not show large deviations. Adding distal mass seems to consistently make the moments slightly more symmetric in the amputee. The prosthetic simulator does not show large changes except the medium setting is slightly more symmetric for the hip and ankle moments. This behavior is observed again with the kinetics. Lower knee heights clearly make the forces more symmetric and the addition of distal mass seems to improve it further. Although the distal mass causes higher metabolic strain (Mattes *et al.*, 2000) on the person, it seems to help balance the asymmetric forces. Prosthetic simulator gait showed no visible deviation in asymmetry for the kinetics. It is possible that combining a lower knee height with a heavier shank may alleviate some of the asymmetric forces that amputees experience in their gait.

Joint kinematics show differences in asymmetries while hip and ankle angles become more symmetric. The knee angles tend to be more asymmetric with lower knee height for the amputee. In the case of the prosthetic simulator, the lowest knee height has more asymmetric hip and knee angles but not in ankle angles. Joint kinematics are also visually perceived and this anomalous behavior is easily detected. Even if these patterns are better overall, there may be issues with the perception of the gait patterns visually.

The hypothesis for this study originated from robotics with the PDW simulation models. From a purely dynamic perspective from the PDW models, it showed that a lower knee height with an asymmetric mass distribution much like an amputee showed better spatiotemporal symmetry (Sushko *et al.*, 2012). This was evident in this study with step length, but step time did not show improvement. We expect simple asymmetric changes in prosthesis design can bring about much better gait patterns for amputees. Lowering the knee height by a few percent (under 26% of knee height) with a slightly heavier shank may improve the kinetic symmetry. This is contrary to the pursuit of lighter prostheses but optimizing and customizing asymmetric prosthesis has potential for better gait patterns. More testing performed with a larger amputee population with and without weighted prostheses would further determine if a combination of lowered knee height and addition of mass can bring out better outcomes in terms of overall asymmetry and quality of gait.

CONCLUSIONS

This study shows the changes in gait asymmetries of spatiotemporal, kinematic, and kinetic parameters for prostheses with asymmetric knee heights. Step length showed improvement for the amputee with and without distal mass. The prosthetic simulators showed some improvement in symmetry, but they did not show specific patterns of improvement. CGAM scores showed that lowering knee heights did improve overall gait pattern symmetry. This study showed that this passive change in knee height has the potential to improve gait patterns for transfemoral amputees and can also be used to improve prosthesis and bipedal robotic designs. Further evaluation with a larger subject population of amputees is required to validate the results of lowered knee heights and combination of heavier shank with lower knee height.

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How to cite this article:

Tyagi Ramakrishnan *et al* (2017) 'Effect of Asymmetric Knee Height on Gait Asymmetry For Unilateral Transfemoral Amputees', *International Journal of Current Advanced Research,* 06(10), pp. 6896-6903.
DOI: http://dx.doi.org/10.24327/ijcar.2017.6903.1037

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