Leg Length Inequality Effects on Ground and Lower Extremity Joint Reaction Forces during Walking

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***Abstract*—Leg length discrepancy (LLD) is caused either due to functional disorder or shortening of bone structure. This disorder could contribute to the significant effects on body weight distribution and lumbar scoliosis to a certain extent. Ground reaction force and joint reaction force are the parameters that can be used to analyse the responses in weight distribution and kinetics changes on the body joints, respectively. The purpose of this study was to determine the effect of Leg Length Discrepancy (LLD) on ground reaction force (GRF) and joint reaction force (JRF) in subjects mimicking LLD. Plywood block was used to mimic the artificial LLD. The height of the plywood was increased up to 4.0 cm with 0.5 cm increment. Hence, eight different height of LLD was considered to investigate which height of LLD initiated the significant effect. The experiment was conducted on ten healthy subjects that are walking on the force plate in two conditions; without load and with a load of 2 kg. Qualisys Track Manager (QTM) system and Visual 3D Software were employed for data processing. The result showed that mean peak vertical GRF and JRF of the shorter leg was found carried more weight than the longer leg during walking without load and walking with the additional load, respectively. Also, mean peak vertical GRF and JRF were found carried more weight during walking with additional load compared to walking without load.**

***Index Terms*— Ground Reaction Force; Joint Reaction Force; Leg Length Inequality; Motion Capture System.**

I. INTRODUCTION

Leg Length Inequality (LLI) or Leg Length Discrepancy (LLD) disorder is a condition where one leg is vertically longer compared to another leg of an individual, where it is caused either by functional disorders or by shortening of bone structures. The disease alters a person body posture which in turns changes the forces acting upon the joints of the lower extremity joints and spine. LLD can be caused by birth conditions such hemihypertrophy; a genetic disorder characterised by overgrowth of one side of the body. There can also be problems from infection or a tumour affecting a normal growth plate [1]. LLD is classified according to the magnitude of the inequality and described as mild, moderate and severe. Mild LLD is less than 3.0 cm, moderate LLD is between 3.0 cm to 6.0 cm, and severe LLD is more than 6.0 cm [2]. Also, mild, moderate and severe LLD have primarily associated with three orthopaedics disorders such as stress fractures, low back pain and osteoarthritis at the knee and hip joints

LLD can be divided into two types: a structural LLD and a functional LLD. Structural LLD is defined as those associated with a shortening of bone structures of the skeletal components of the lower limb, while functional LLD can be defined as those that caused by joint contracture which results in inequality in lower limb length [3]. LLD is classified according to the magnitude of the inequality and described as mild, moderate and severe. Mild LLD is less than 3.0 cm, moderate LLD is between 3.0 cm to 6.0 cm, and severe LLD is more than 6.0 cm [4]. However, differences in length of over 2.0 cm are very rare.

Pereira et al. found that patients with mild LLD of 0.5 cm to 2.0 cm can present higher values of vertical GRF at the shorter leg compared to the longer leg [5]. After the simulation of the LLD, weight distribution is greater in the shorter leg compared to the longer leg [6]. It is generally agreed that a discrepancy of 1 cm of LLD is clinically significant [7]. Walsh et al. reported that correction of pathological foot position from maximum pronation to supination resulted in a change in limb length of 1 cm [8]. Subotnick suggests that LLD more than 0.6 cm is sufficient enough to cause chronic repetitive overuse injuries on the short leg in runners [9].

LLD also can affect the lumbar spine by causing lumbar scoliosis and also can affect a pelvic obliquity which can induce scoliosis of the spine [10]. Giles and Taylor [11] have treated 50 LLD patients having low back pain by using shoe lifts resulting in decreased low back pain symptoms and increased the scope of motion. They observed that LLD of more than 1 cm has more common in patients with low back pain. There is another study found that shoe lifts can reduce the low back pain of a patient who has chronic low back pain and severe LLD [12].

Moreover, Brunet e. al [13] reported that LLD with at least 1 cm differences had a 46.2% rate of a stress fracture, while for those with LLD from 1.5 cm to 2.0 cm differences had 67% rate of a stress fracture. The stress fractures were most affected in the femur, tibia, and metatarsals. Usually, the stress fractures most occurred at the long leg [3]. Murray and Azari [14] state that mild LLD may be a contributor to Osteoarthritis of the hip and lumbar spine, and that it deserves to be rigorously studied to decrease Osteoarthritis burden of disease. Besides, through literature review, it is found that a person can bear LLD from 1.0 cm to 5.0 cm to avoid major problems like lower back pain, muscle or ligament injury [15]. It is generally agreed that a discrepancy of 1 cm of LLD is clinically significant [16]. Therefore, to explain the effects of LLD disorder, the evaluation of changes in joint forces for a different level of LLD should be investigated. This study aims to gain an understanding of how LLD level influences ground reaction force and the joint reaction force of the lower limb during walking.

II. EXPERIMENT

A. Subjects

Ten volunteer subjects from University Malaysia Perlis have been recruited for this study (five males and five females) with ages range between 22 years old and 23 years old. Their height and mass were recorded, and their BMI was calculated to make sure they are in normal BMI. Normal BMI for men is ranging between 20.0 and 24.9, while for women is between 19.0 and 23.9.

B. Experiment and Setup

The material used for this project is plywood with 0.5 cm of thickness. The plywood is cut into 40 cm x 20 cm dimension which it will fit for one foot only which is left foot. For each height of the LLD, ten pieces of plywood are used where the plywood will be put along the platform. Since, there are eight different height of LLD that will be analysed (0.5 cm, 1.0 cm, 1.5 cm, 2.0 cm, 2.5 cm, 3.0 cm, 3.5 cm and 4.0 cm), then 80 pieces of the plywood are used. The height, *h* of the LLD is increased by adding up the plywood pieces from a height of 0.5 cm until up to 4.0 cm. To investigate the influence of additional load (instead of self-weight) of GRF and JRF response, the backpack was used to carry 2 kg of load. The arrangement of plywood is shown in Figures 1 and 2.

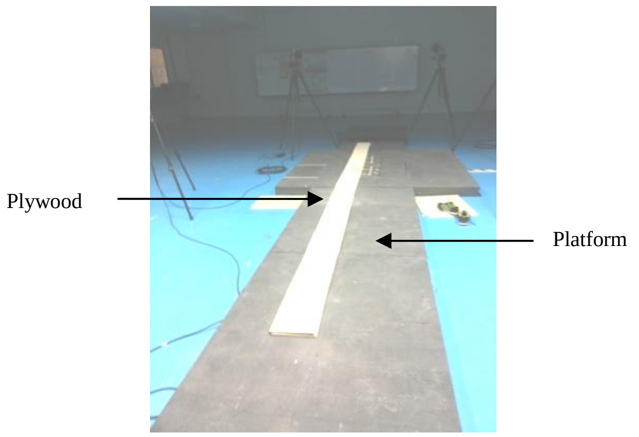


Figure 1: Arrangement of plywood block on the platform

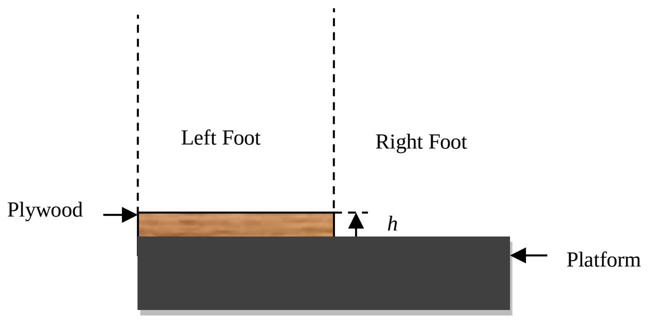


Figure 2: Long leg was set on left foot with LLD level, *h*

The experiment was conducted by using Qualisys Track Manager (QTM) Software analysing the force through the joints of the lower limb. The software is used to collect the data of the subjects and visualise the models either in three-dimensional (3D) models or two-dimensional (2D) models. Before starting the experiment, calibration of the cameras is required to define the measurement volume. Two force plates were embedded at the centre of a platform. The force plates are used for the acquisition of GRF of the right and left leg during the walking phase. The force plates (AMTI force platform) are connected to the computer and are acquired via Qualisys Track Manager (QTM) software**.** A five-camera motion capture system (ProReflex infrared, Qualisys) is used to capture the subject's motion during the walking phase.

C. Protocol

All data were collected and analysed in two different conditions; 1) walking without load; 2) walking with a load. 2 kg of the load was used in this experiment, and the subjects need to wear backpack together with the load. All subjects are barefooted during their participation in this study. The subjects need to walk on the plywood that has eight different heights along the walkway platform with barefoot. A brief explanation regarding the experiment and instruments used is provided by the teaching engineer as the guidance and cautions of the procedures. Placement of the markers with the tape and tight-fitting cloth is prepared for the subjects to avoid any uprooted marker placement while experimenting. Only lower limb markers are needed for the data collections. All the marker placement was followed by the Visual 3D conventional gait model.

D. Data Analysis

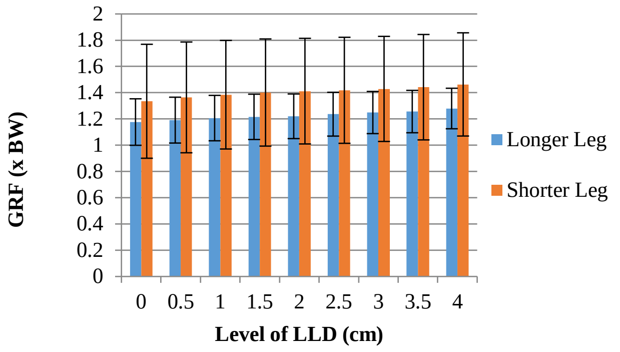
A set of vertical GRF data and JRF data for each subject was analysed, giving a total of 16 sets in walking performance for both walking conditions. QTM software was used to determine the magnitude of forces, durations, acceleration and velocity of the selected reaction force parameters automatically. For analysis of GRF data, the variable of interest in this study is the vertical GRF related with toe-off. The left leg can be assumed as longer leg (by adding up the different height of plywood), while the right leg can be assumed as a shorter leg. The JRF data also can be derived from 3D models output of QTM Software. All the joints (hip, knee and ankle) were determined in 3D models continuously during the gait cycle. The static model is needed to act as calibration model. The bone of the subjects was created in Visual 3D software to visualise the model based on marker placement.

The data smoothing methods for both GRF and JRF were selected after all data has been exported to the Visual 3D software. The data were filtered using a second-order, recursive Butterworth digital filter at cutoff frequencies of 20 Hz. After the initial data processing, average GRF and JRF data were created from normalised each data. Force data were normalised to body weight (BW) of the subject.

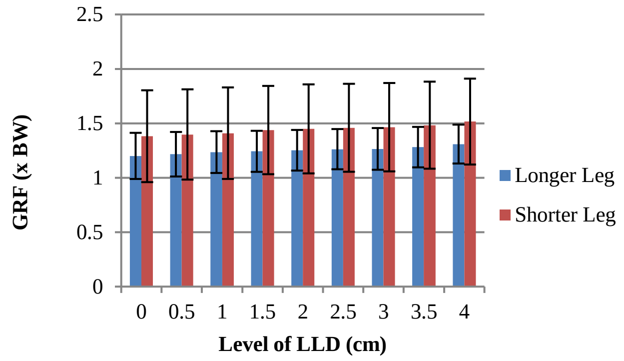
III. RESULT AND DISCUSSIONS

Figure 3 shows the mean peak vertical GRF during stance phase at the longer leg and shorter leg when walking without load and walking without load. The data for all subjects was normalised by dividing the force by body weight (BW) of each subject. The graph 3(a) shows the force generated at LLD level of 4 cm is the highest compared to other levels for both longer leg and shorter leg with a mean peak value of 1.2796±0.1543 and 1.4631±0.3932, respectively. The graph

3(b) shows the force generated at LLD level of 4 cm is the highest compared to other levels for both longer leg and shorter leg with a mean peak value of 1.3094±0.1786 and 1.5159±0.3945, respectively.



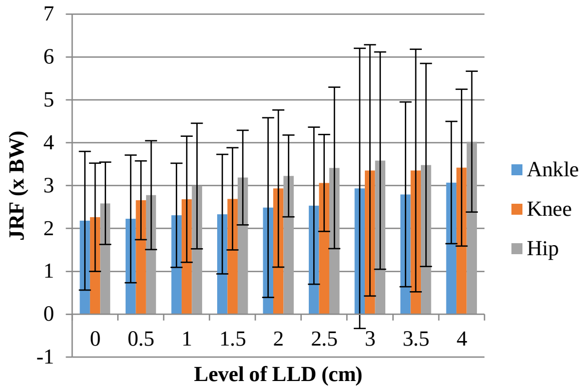
(a)



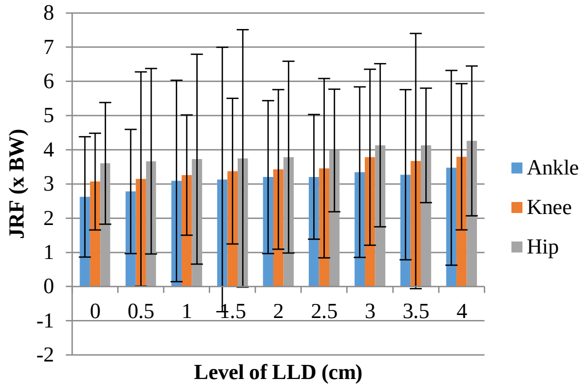
(b)

Figure 3: (a) Mean peak vertical GRF during stance phase at the longer leg and shorter leg during walking without load, (b) Mean peak vertical GRF during stance phase at the longer leg and shorter leg during walking with 2 kg of load

Figure 4 shows joint reaction force of ankle joints longer leg during walking without load and with the load. From the graph (a) and (b), it shows the force distribution is increased for both legs at all level of LLD. The graph shows the force generated at all joints on the longer leg is the highest during walking with load compared to walking without load. For graph (a), by comparing the standard deviation (SD) for all level of LLD at each joint, SD at 3 cm present highest SD for ankle, knee and hip joint compared to another level. For graph (b), SD at 1.5 cm present highest SD for ankle joint and hip joint compared to another level. Meanwhile, SD at 3.5 cm present highest SD for the knee joint. With the highest value of SD, it indicates the data is spread out over a wider range of values.



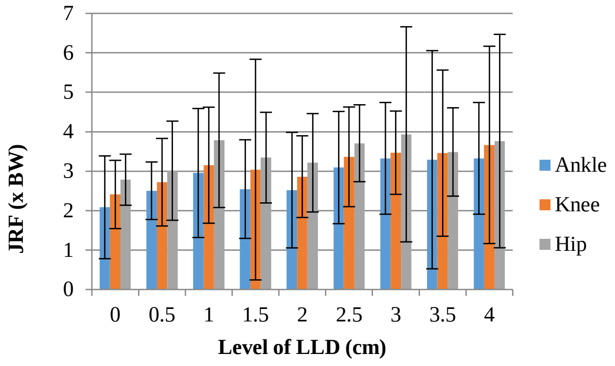
(a)



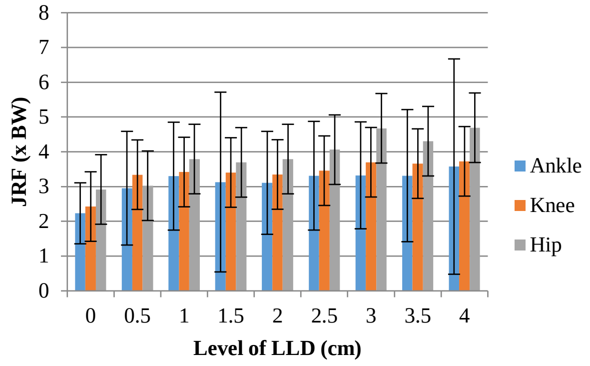
(b)

Figure 4: Joint reaction force at the ankle, knee and a hip joint for the longer leg; (a) walking without load, (b) walking with a load

Figure 5 shows joint reaction force of ankle joints shorter leg during walking without load and with the load. From the graph (a) and (b), it shows the force distribution is increased for both legs at all level of LLD. The graph shows the force generated at all joints on the shorter leg is also highest during walking with load compared to walking without load. For graph (a), by comparing the standard deviation (SD) at each joint, SD at 3.5 cm and 1.5 cm present highest SD for ankle joint and knee joint compared to another level, respectively. Meanwhile, SD present highest value for the hip joint at 3 cm. For graph (b), SD at 4 cm presents highest SD for ankle compared to another level. Meanwhile, SD is constant for knee joint and hip of the shorter leg for all level of LLD. With the highest value of SD, it indicates the data is spread out over a wider range of values.



(a)



(b)

Figure 5: (a) Joint reaction force at the ankle, knee and hip joint for the shorter leg; (a) walking without load, (b) walking with a load.

Based on the results, it is shown that the mean peak vertical GRF exerted on the ground through the legs is greater in shorter leg compared to longer leg for all levels of LLD during walking without load and walking with load, respectively. From all graphs above, the force exerted on longer leg, and a shorter leg for each level of LLD is increased. This result is consistent with Pereira et al. [4] as they found that subjects with mild LLD of 0.5 cm to 2.0 cm presented higher values of vertical GRF at the shorter leg.

Furthermore, distribution of joint reaction forces at ankle joints, knee joints and hip joint also represent higher forces at shorter leg when compared with joint reaction forces at the longer leg for both walking without load and walking with load, respectively.

By comparing the weight distribution between walking without load and walking with load, walking with 2 kg of load activities shows higher forces exerted compared to walking without load activities for both legs. It can say that load with small as 2 kg of weight still can affect the weight distribution on LLD. This finding agrees with Swaminathan et al. [5] where they claimed that weight distribution increased in the shorter limb when LLD was simulated on a subject that caring load. Besides, it is known that walking velocity and time can affect the magnitude of GRF and JRF. In this way, the force is directly proportional to walking velocity and inversely proportional to time impact with the ground. Hence, the increment of the force might be due to short impact time between the surface of foot and ground.

However, when comparing the forces distribution between without load and with a load for each leg, the finding is not consistent. For longer leg, both ankle joint and knee joint present higher force exerted during walking with a load. However, at hip joint the distributions are almost constant for both conditions until, at 4 cm, the force exerted at the hip joint is higher during walking without a load than walking with a load. For shorter leg, we found ankle joint and hip joint exerted more forces during walking with load compared to walking without load. However, knee joint present higher force during walking without load compared to walking with a load.

The GRF and JRF reflect the vertical forces and shear forces acting on the surface of the ground. During the vertical GRF at toe-off, the plantar flexors muscle are in an active condition which causing a second peak of GRF greater than body weight. This demonstrates that the body's centre of mass is being accelerated upwards to increase its upward velocity. Then, the weight drops to zero as the opposite leg takes up the body weight. However, reaction force has high sensitivity to any action or reaction which it is altering the GRF and JRF magnitude, such as arm lifting, which at the same time it can diminish the second peak force to less than body weight.

IV. Conclusion

This paper presents a study on the influence of LLD on the ground and the joint reaction force of human body that lead to the significant clinical effects. The result of GRF and JRF responses suggest that the LLD level and walking condition influenced the force distribution. Imbalance in weight distribution between both legs could affect postural stability, especially during walking activities. However, some limitations were associated to the present experiment. For this project, only ten subjects are recruited to run the experiment. The samples are limited as all the subjects are from the same university population. Thus, the result only can be used among university population. Samples can be varied if we can take into account the civilian populations who have a variety of ages and backgrounds. Besides, the weight of the load that was used in the experiment is limited to 2 kg for all subjects. A more large weight load could be used to identify how much load could give more significant effects on LLD in term of walking posture and gait stability.

Acknowledgement

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