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Lower extremity joint reaction forces and plantar fascia strain responses due to incline and decline walking

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Purpose: The present study aims to investigate the effect of incline and decline walking on ground and joint reaction forces (JRF) of lower extremity and plantar fascia strain (PFS) under certain surface inclination angles. *Methods*: Twenty-three male subjects walked on a customized platform with four different surface inclinations (i.e., 0, 5, 7.5 and 10°) with inclined and declined directions. The motion of the ten reflective markers was captured using Qualysis motion capture system (Qualysis, Gothenburg, Sweden) and exported to a visual three-dimensional (3D) software (C-motion, Germantown, USA) in order to analyze the GRF, JRF and PFS. *Results*: The results found that the peak vertical GRF is almost consistent for 0 and 5° inclination slope but started to decrease at 7.5° onwards during decline walking. The most affected JRF was found on knee at medial-lateral direction even as low as 5 to 10° inclination for both walking conditions. Furthermore, the findings also show that the JRF of lower extremity was more affected during declined walking compared to inclined walking based on the number of significant differences observed in each inclination angle. The PFS was found increased with the increase of surface inclination. *Conclusions*: The findings could provide a new insight on the relationship of joint reaction forces and strain parameter in response to the incline and decline walking. It would benefit in providing a better precaution that should be considered during hiking activity, especially in medial-lateral direction in order to prevent injury or fall risk.

Key words: *surface inclination, incline/decline walking, plantar fascia strain, joint reaction forces, lower extremity joints*

1. Introduction

Daily life locomotion in the community usually requires demanding tasks for example uphill or downhill movement [1]. Slope walkways often used to assess almost every public building and be an option to avoid steps and stairs [2]. Walking on slope surface can also be considered as an important aspect of mobility, however, the exposure to the slope surface can bring out modification of kinetic and kinematics parameters. Thus, both uphill and downhill walking might contribute to the injury as well [3]. Hence, biomechanical adaptation is crucial to be understood to ensure each individual gait safety.

Kinetic and kinematic modifications of lower extremity depending on surface conditions that led to different biomechanical responses including muscle activity [4]. Joint reaction force (JRF) determination in incline surface investigation is significantly related to muscle

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response [4]. Changes in JRF also is influenced by the ground reaction force (GRF) obtained [5]. Foot contact with floor surface could contribute to several physical injury risks. Ankle joint twisting caused by restricted foot movement can result to strain from recurrent foot impact or loading, as well as muscle weariness or inflammation. The strain or inflammation of plantar fascia might lead to plantar fasciitis. Plantar fasciitis is one of common painful disorder that related to gait movement [6].

Plantar fascia is a thick and fibrous layer of connective tissue (aponeurosis) that adheres to the plantar surface of metatarsophalangeal joints which come from the medial tubercle of the calcaneus embedded into the deep soft tissue of the forefoot [7]. The function of plantar fascia is to support the arch of the foot during loading [8] and it remains the most important arch stabilizing structure. Plantar fascia elongates with increasing loads, and stores this elastic energy, serving as a shock absorber [9]. These mechanical properties are linked with the manner of its insertion into the medial calcaneus. Eventually, the plantar fascia has a vital role in re-supination of the foot during the propulsive period of the stance phase of gait [10]. Excessive plantar fascia elongation may lead to injury due to the abnormal foot motion during gait. This elongation can be analyzed and investigated as strain.

In recent years, numerous studies were undertaken to investigate the effects of incline surface during standing [11], [12] and locomotion; either running [13], [14] or walking [15], [16]. In particular, a number of researchers have sought to determine the effect of inclined surface to the kinetic parameters in term of force variable. Telhan et al. [3], who studied the three components at GRF during slope running, reported that the increase of peak force can only be seen in vertical component of GRF during declined running while the non-vertical component of GRF show no difference. Damavandi et al. [17], who investigated GRF in cross-slope and level gait, also found that the maximum peak of force was observed during inclined running compared to other conditions.

Furthermore, several studies analyzed the lower limb joint forces using musculoskeletal model but the number was quite limited [4], [18], [19] Accessible research on sloped walking includes only minimal information. For instance, Kuster et al. [18] and Haight et al. [19] only consider knee joint reaction on one specific inclination angle in order to prove that knee joint force was able to be controlled by the spatio-temporal parameter during slope walking [18]. Besides that, Alexander and Shwameder analyzed the lower limb joint force of hip, knee and ankle during uphill and downhill walking at different inclination and level walking [4]. However, the issues discussed were only related on lower limb joint forces and not expanded into each anatomical plane.

To the best of our knowledge, only a few studies to date have assessed the lower limb joint forces in three anatomical planes and relationship of the kinetic parameters in terms of force and plantar fascia strain towards incline and decline walking. At what angle of slope and which part of lower limb joints that most affected due to incline and decline walking still unclear. Therefore, the purpose of this study was to investigate the effect of incline and decline walking on the lower extremity joint reaction forces (JRF) and plantar fascia strain (PFS) under certain surface inclination angles.

2. Materials and methods

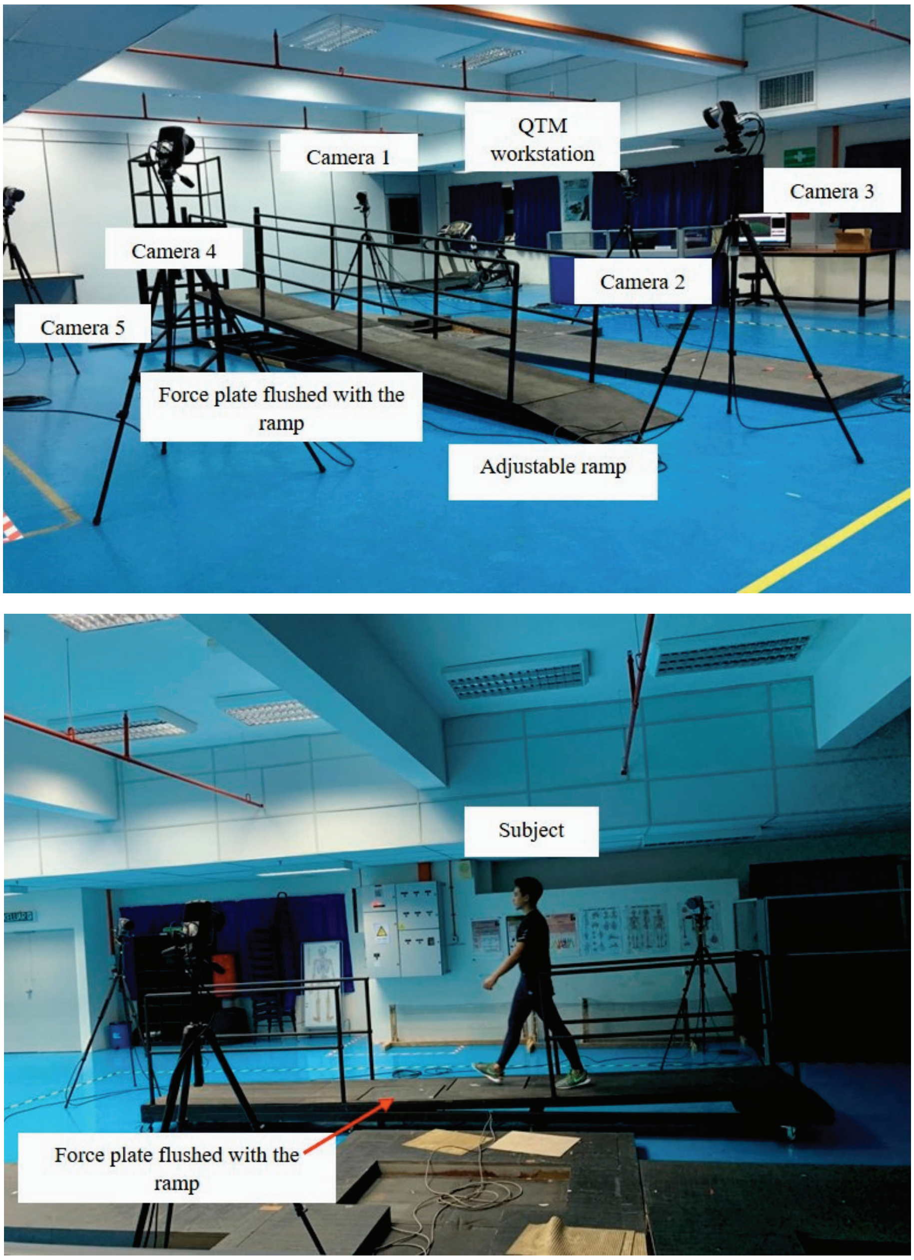
2.1. Participants

Twenty-three healthy subjects from university population that had mean age of 24 ± 1.2 years old with normal body mass index (BMI) category were selected to participate in this experiment. Participants with previously musculoskeletal injury or orthopedic abnormality were excluded from this experiment in order to prevent any dissimilarity in the movement and difficulty potential to perform the walking activity. Each participant voluntarily agreed to participate in the study and signed the consent form prior to participation. This experiment was approved by the Ethic Committee of the Universiti Malaysia Perlis.

2.2. Equipment and devices

A customized wooden slope platform with adjustable angle, as shown in Fig. 1, was developed for this experiment. The slope is a walkway platform with 1 m wide and 5 m long. There are spaces created for two force plates to be embedded on the slope that is flush with the walking surface. The inclined angle of ramp surface can be adjusted to 0, 5, 7.5 and 10°. The 5° angle was chosen to meet the maximum slope allowed under Malaysian Standard for Universal design [Clause 7.2(a), MS 1331:2003 and Clause 5.1(b), MS 1184:2002]. Five Oqus motion capture cameras (Qualysis, Gothenburg,

(a)



(b)

Fig. 1. Overview of the experimental procedure: (a) equipment arrangement for the experiment, (b) subject walking on the ramp

Sweden) and two force plates (Bertec Corp., Columbus, Ohio, USA) with frequency of 200 Hz were used in the experiment. The equipment arrangement and demonstration of subject walking on the ramp are shown in Figs. 1a, b, respectively.

Ten reflective markers with diameter of 20 mm were used in the experiment. The marker placement is a modification version of lower limb "Plug-in Gait" marker set. The markers were attached at right anterior superior iliac spine (RASI), left anterior superior iliac spine (LASI), right posterior superior iliac spine (RPSI), left posterior superior iliac spine (LPSI), right lateral thigh (RTHI), right lateral knee (RKNE), right lateral shank (RTIB), right lateral malleolus (RANK), right second metatarsal head (RTOE) and right center of calcaneus (RHEE), as shown in Fig. 2. Specific holes were cut in the shoe for RTOE and RHEE locations in order to ensure the reflective markers were adhered directly to the skin. This marker set-up makes it possible for the tracking markers to be recorded by the cameras and measure the plantar fascia length [20].

The motion of markers was captured using Qualysis motion capture system (Qualysis, Gothenburg, Sweden) and exported to a visual three-dimensional (Visual3D) software (C-motion, Germantown, USA) in order to obtain the GRF, JRF and PFS.

(a) (b)

Fig. 2. Marker placement on the subject's body:
(a) anterior view of marker placement,
(b) posterior view of marker placement

2.3. Procedure

Prior to the experiment, participants' anthropometry details such as height, weight, left and right width for both knee and ankle were measured and collected. Then, the participants first walked on the incline platform to familiarize with the conditions of the experiment. A reference static trial was recorded when the participants stand upright in double-leg support posture in order to identify the neutral position of the joint [21]. Once the static position was recorded, participants were asked to walk at their comfortable speed wearing similar shoes, on three different angles of sloped platform (0, 5, 7.5 and 10°), with incline and decline directions. Trial was accepted if all markers were well visible and foot-to-force plate contact was obtained without obvious alteration on walking stride.

2.4. Data analysis

Kinematics data obtained were further processed using Qualysis Track Motion system (Qualysis, Gothenburg, Sweden). Processed kinematic and force plate data were imported into the Visual3D software (C-motion, Germantown, USA) to evaluate the JRF of lower limb. The musculoskeletal model used in this study was a standard model (Plug-in lower limb) available in the software. "Plug-in Gait" uses a Direct (Non-Optimal) Pose Estimation for computing the position and orientation of each segment based on a set of 3 tracking markers. The plantar fascia strain was calculated using the collected kinematic data.

During analysis, the trajectories of the reflective markers were filtered at 6 Hz using a low-pass filter. The data was investigated for the whole stance phase of walking gait which started from foot strike until toe off. The start and end of the stance phase was evaluated by observing the pattern of GRF. The parameters measured and analyzed were: 1) GRF (the force exerted by the ground on the whole body), 2) JRF (the force exerted at each joint namely hip, knee and ankle with respect to anatomical coordinate system in three anatomical planes (frontal, sagittal and transverse plane)); and 3) PFS (the change in length during the stance phase divided by the original length of the relative position distance between the calcaneus and first metatarsal markers). The PFS measurement method was adopted from previous studies [20], [22], [23].

Means and standard deviations of the parameters measured were evaluated for each inclined angle. The means and standard deviations were evaluated using Shapiro–Wilk normality test. The result showed that the data obtained were not normally distributed. Differences for each parameter measured were analyzed using the non-parametric test. The statistical analysis was tested by comparing the case between level walking and incline/decline walking. The Kruskall–Wallis test with statistical significance was accepted at $p < 0.05$. The Kruskall–Wallis test was chosen as it is the most suitable test in statistical analysis for investigating the differences of two or more means for abnormally distributed data. Statistical Package for Social Science (SPSS) version 17.0 (IBM, Armonk, NY, USA) was utilized to perform the statistical analysis.

3. Results

3.1. Effect of incline and decline walking on ground and joint reaction forces

The first part of this study was to investigate the influence of sloped walking to the ground and lower extremity joint reaction forces. The result obtained were normalized to the subject's body weight. In Figure 3, the peak vertical GRF that produced during incline and decline walking for overall stance phase is shown. It is apparent in the Figure that the peak vertical GRF is almost consistent for 0 and 5° inclination but started to decrease at 7.5° onwards during decline walking but almost constant during incline walking. The highest value of peak GRF was obtained during decline walking at 5° slope with 10.765 ± 1.367 (× BW) N and the lowest peak GRF was found during decline walking at 10° slope with 6.779 ± 3.645 (× BW) N. Further statistical analysis on the peak vertical GRF found that there is statistically significant different of GRF exerted during both incline and decline walking as calculated using Kruskall–Wallis test with *p*-value = 0.006.

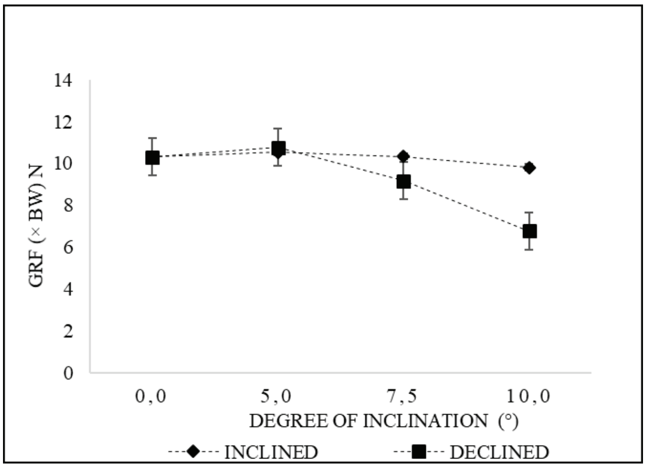


Fig. 3. Peak vertical GRF responses during incline and decline walking

In order to assess the effect of incline and decline walking on joint reaction forces, Tables 1 and 2 provide the peak JRF of lower extremity responses with respect to inclination angles. The JRF analysed in this study are in three directions with respect to anatomical coordinate system; JRF in anterior-posterior (JRF_{AP}), JRF in medial-lateral (JRF_{ML}) and JRF in proximal-distal (JRF_{PD}). The JRFs obtained were also used to calculate a resultant force (JRF_R). As shown in Table 1, during incline walking, JRF_{AP} of ankle was begin to affected at 7.5° inclination ($p < 0.05$) compared to level (0°) walking. However, the ankle JRF_{ML} was only affected at 10° of incline walking ($p < 0.05$). Whereas, no significant different ($p > 0.05$) was found for ankles JRF_{PD} and JRF_R due to incline walking for all inclination angles. Interestingly, the most affected JRF due to incline walking was found on knee joint particularly in the peak JRF_{ML}. The JRF_{ML} has significant different ($p < 0.05$) during incline walking compared to level walking as low as 5° inclination. In contrary, the peak JRF_{AP}, JRF_{PD} and JRF_R of knee were found not influenced by surface inclination where there are no significant different for all inclination angles ($p > 0.05$). Moreover, the peak JRF at hip joint in all directions were found not affected by inclined surface as the statistical analysis results there is no significant different ($p > 0.05$) obtained.

Furthermore, the peaks JRF_{AP} and JRF_{ML} of ankle during decline walking were found not affected ($p > 0.05$) for all inclination angles as compared to level walking as presented in Table 2. On the other hand, the JRF_{PD} and JRF_R of ankle show there is significant different ($p < 0.05$) at 10° inclination of decline walking, which is in contrary to the results of incline walking. However, the data of knee JRF particularly in medial-lateral direction under decline walking was found similar to the finding during incline walking. The knee JRF_{ML} was obtained has significant different even at 5° inclination ($p < 0.05$). Moreover, the knee JRF_{PD} was also found sensitive to the decline walking compare to level walking starting at 7.5° inclination ($p < 0.05$). Whereas, no significant difference for

Table 1. Peak JRF of lower limb during incline walking

	Degree of Inclination [°]	JRF_{AP} (× BW) N	JRF_{ML} (× BW) N	JRF_{PD} (× BW) N	JRF_R (× BW) N
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ±SD
ANKLE	0.0	2.716 ± 1.142	2.074 ± 1.295	9.909 ± 0.580	10.451 ± 0.719
	5.0	2.450 ± 1.299	3.339 ± 1.528	10.120 ± 0.588	10.741± 0.582
	7.5	1.119 ± 0.441*	3.078 ± 0.420	10.017 ± 0.623	10.476 ± 0.620
	10.0	1.203 ± 1.384*	3.149 ± 0.864*	9.698 ± 1.017	10.143 ± 1.169
KNEE	0.0	1.477 ± 0.646	1.640 ± 0.463	9.719 ± 0.601	9.946 ± 0.702
	5.0	1.919 ± 0.862	2.892 ± 1.504*	9.901 ± 0.621	10.109 ± 0.707
	7.5	1.103 ± 0.540	2.069 ± 0.537*	9.770 ± 0.542	9.946 ± 0.596
	10.0	1.501 ± 1.503	2.607 ± 1.245*	9.334 ± 1.117	9.626 ± 1.115
HIP	0.0	1.144 ± 0.417	1.921± 0.683	8.706 ± 0.590	8.915 ± 0.681
	5.0	1.306 ± 0.526	2.584 ± 1.274	8.871 ± 0.596	9.241 ± 0.619
	7.5	1.155 ± 0.577	1.893 ± 0.297	8.689 ± 0.571	8.854 ± 0.546
	10.0	1.693 ± 1.176	2.464 ± 1.485	8.259 ± 0.974	8.566 ± 1.007

* Significantly different in comparison with level walking with *p*-value < 0.05.

Table 2. Peak JRF of lower limb during decline walking

	Degree of Inclination [°]	JRF_{AP} (× BW) N	JRF_{ML} (× BW) N	JRF_{PD} (× BW) N	JRF_R (× BW) N
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ±SD
ANKLE	0.0	2.716 ± 1.142	2.074 ± 1.295	9.909 ± 0.580	10.451 ± 0.719
	5.0	2.391 ± 1.324	2.414 ± 1.927	10.433 ± 0.600	10.832 ± 0.659
	7.5	2.204 ± 0.913	2.243 ± 1.246	8.582 ± 1.730	8.955 ± 1.794
	10.0	2.016 ± 1.074	2.071 ± 1.217	6.731 ± 3.739*	7.078 ± 3.774*
KNEE	0.0	1.477 ± 0.646	1.640 ± 0.463	9.719 ± 0.601	9.946 ± 0.702
	5.0	1.567 ± 0.814	2.986 ± 1.737*	9.999 ± 0.711	10.360 ± 0.656
	7.5	1.955 ± 0.497	3.731 ± 1.642*	7.600 ± 1.643*	8.499 ± 1.787
	10.0	2.344 ± 1.075	4.475 ± 1.729*	5.201 ± 3.533*	6.638 ± 3.764
HIP	0.0	1.144 ± 0.417	1.921 ± 0.683	8.706 ± 0.590	8.915 ± 0.681
	5.0	1.019 ± 0.423	3.517 ± 0.600*	8.795 ± 0.645	9.272 ± 0.534
	7.5	1.462 ± 0.750	3.332 ± 0.998*	6.876 ± 1.712*	7.481 ± 1.734
	10.0	1.905 ± 1.481	3.148 ± 1.760*	4.956 ± 3.634*	5.689 ± 3.692*

* Significantly different in comparison with level walking with p-value < 0.05.

decline walking at knee JRF_{AP} and JRF_R ($p > 0.05$). It is apparent from Table 2 that the most affected joint due to decline walking is hip. The JRF of hip in medial-lateral, proximal-distal and resultant directions were found have significant differences ($p < 0.05$) compared to level walking starting at 5, 7.5 and 10° respectively. However, hip JRF_{ML} and JRF_{ML} were not influenced by decline walking for all inclination angles ($p > 0.05$).

3.2. Effect of incline and decline walking on normalized plantar fascia strain

In Figure 4, the peak of PFS during incline and decline walking with respect to different inclination angles is shown. From the figure, it can be seen that the peak PFS is increasing as the inclination angle

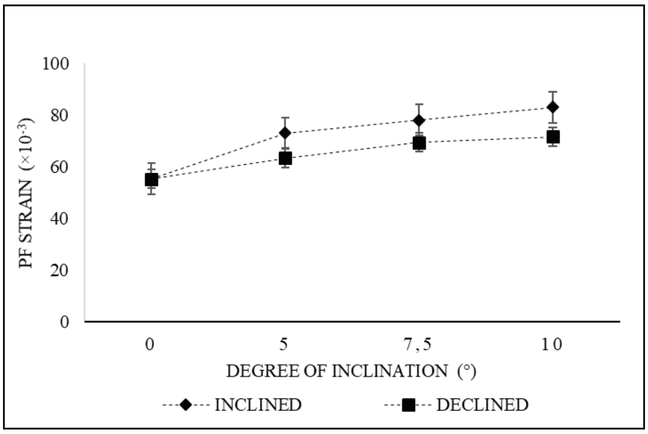


Fig. 4. Comparison of peak plantar fascia strain during incline and decline walking

increased for both incline and decline walking conditions. PFS was found lowest during level walking at $(55.231 \pm 9.746) \times 10^{-3}$ and the measured PFS during incline walking is always higher compared to decline walking for all inclination angles.

4. Discussion

This study was set out with the aim of assessing the effect of incline and decline walking on the ground reaction force and lower extremity joint reaction forces as well as plantar fascia strain. The reaction forces obtained were involving joint of lower limb, i.e., hip, knee and ankle in sagittal, transverse and frontal plane. The results of this study show that the peak vertical GRF is almost consistent at 0 and 5° inclination/declination and started to decreased with the increase of slope at 7.5 to 10° inclination/declination. These results are in line with the findings of Slider et al. [24] and Chen Wen et al. [25], who reported the similar trend for peak push off loading during slope walking on different slope angles.

The most important finding in this study is that the JRF of knee in medial-lateral direction was found the most sensitive to the surface inclination during incline and decline walking even at the lowest inclination angle which is 5°. It seems possible that these results are due to the increasing of maximum knee extension during slope walking [26]. As a modified hinge joint, knee enable flexion and extension generated by both rolling and gliding movement of the femur on tibia. Specifically, the flexion and extension motion are caused by the rolling action, meanwhile, the gliding action keeps the femoral condyles fixed over the tibial condyles, providing optimum bony, weight-bearing support for the femur in all knee postures. To achieve the most stable positions, the knee must be in full extended state which can be obtained by medial rotation action of femur in relation to tibia. The medial rotation is resulted from the rotation of lateral condyle of the femur followed by medial condyle [27]. This movement explained the significant different observed in JRF_{ML} of knee for the tested inclination angles which indicate the influence of surface inclination to JRF during both incline and decline walking conditions.

Furthermore, another important finding is that the JRF of the lower limb joint (i.e., hip, knee and ankle) was found more affected during decline walking compared to incline walking based on the number of statistically significant differences ($p < 0.05$) obtained in JRF_{ML}, JRF_{PD} and JRF_{R}. The JRF of knee and hip particularly in medial-lateral direction (JRF_{ML}) were found to be sensitive to decline walking for all declination angles (5, 7.5 and 10°). This result seems to be consistent with another research which found that the related JRF is influenced by the slopes over the stance phase [28]. In decline walking locomotion with increasing slopes, it appears that a pelvis strategy in medial-lateral was used to limit the loads and motions in the lower limb joints [28], [29]. In addition, during decline walking, the hip was upwardly moved because of height differences between the feet positions during initial contact result to more laterally direction of GRF, that influence the JRF exerted [28], with respect to stance limb.

Moreover, the finding also can be explained by the fact that the changes of related JRF is required in order to achieve more flexion at knee by increasing the moment at knee to meet the requirement for decline walking on increasing slope. This is because the flexion at knee of stance phase is during decline walking was reported to be approximately by 4° greater than during level walking [30]. The affected peak JRF ($p < 0.05$) in lower limb that observed is also probably due to the adaptation of the leg in order to ensure stability and postural balance during decline walking [17].

Besides, this study also found that the peak PFS is increasing with the increase of inclination angle for both incline and decline walking. Plantar fascia main purpose is to support the foot's arch bearing and absorbs the contact loading of foot during gait [31]. The elastic characteristic of plantar fascia enables the purpose of this ligament can be achieved. For a material demonstrating elastic properties, the failure force increases as the rate of strain increases, but the elongation at failure reduces as the rate of strain increases [32]. The function of plantar fascia is closely related to kinetic and kinematic modification in adapting the walking surface to prevent injury or fall. It seems that, a reduced inversion or increased eversion of foot during incline walking enabled the ankle dorsiflexion during incline walking [33]. In addition, both incline and decline walking require a greater ankle flexion during stance phase for toe clearance [34]. Thus, the result of the present study can be explained by the statement suggested by Cheng et al. [35] which stated that the rising of toe dorsiflexion angle and Achilles tendon force increased the PFS.

5. Conclusions

The present study was designed to determine the effect of surface inclination on reaction forces and strain parameters during incline and decline walking. This study has identified the JRF on knee at medial-lateral direction was affected with the surface inclination angle in both incline and decline walking. Moreover, the JRF was also found to be more influenced by surface inclination angle during decline walking compared to incline walking based on the number of statically significant differences obtained in JRF_{ML}, JRF_{PD} and JRF_{R} on knee, hip, and ankle. This research also has shown that the PFS is increasing with the increase of surface inclination. Both, the joint reaction forces and PFS, are changing accordingly to reflect the surface inclination requirement during slope walking. Taken together, these findings also suggest a better precaution should be undertaken during slope gait, especially in decline slope walking and medial-lateral direction to prevent injury or fall risk. This study could contribute a major role in determining a proper walking strategy on inclined surface for a safe and convenient slope movement. Also, this project could potentially give an insight for further improvement of human mimicking system that will allow for better interaction between human and machines.

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