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Correlation between Postural Stability and Lower Extremity Joint Reaction Forces in Young Adults during Incline and Decline Walking

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Abstract: Postural stability may be affected during slope walking, as there are different body kinetics and kinematic responses compared with level walking. Understanding body adaptations toward different inclinations is essential to prevent the risk of injury from falls or slips. This study was conducted to determine the correlations between stability parameters and loading response in terms of joint reaction force at the lower-extremity joints during inclined and declined walking. Twenty male subjects walked in the level, incline, and decline directions on a custom-built platform at three different slope angles (i.e., 5°, 7.5°, and 10°). To determine the ground reaction force (GRF), joint reaction force (JRF), center of pressure (COP), and center of mass (COM), a motion capture system was used to read the data of the ten reflective markers and transfer them to visual three-dimensional (3D) software. Pearson's correlation test was performed with statistical significance set at $p < 0.05$ to evaluate the correlation of the required coefficient of friction (RCOF), postural stability index (PSI), and COP-COM distance with the JRF. This study has identified that the JRF changes in opposition to the changes in the RCOF during the initial strike during incline and decline walking, as JRF increases, the RCOF decreases with different strengths of correlation. There is also a strong positive correlation between the PSI and JRF in the proximal–distal direction, where the JRFs change in accordance with the change in the PSI, and the JRF increases with the increment of PSI. In addition, the JRF of the lower extremity also changed in a manner similar to the COP-COM distance in the medial–lateral direction. Overall, each stability parameter was correlated with the JRF of the lower-extremity joints in different directions and strengths. This study demonstrated that slope walking is particularly affected by surface inclination in terms of stability and loading. Therefore, this research can serve as a basis for future studies on slopes, as there is no specific basis for a maximum degree of inclination that is safe and suitable for all applications.

Keywords: surface inclination; stability; lower-extremity joint reaction force; slope walking

1. Introduction

Slope walking, commonly referred to as hill walking or uphill and downhill trekking, has several advantages for both physical and emotional health. This common outdoor activity requires navigating a variety of topographies with elevation variations, providing a unique and rewarding experience for enthusiasts. Incline walking requires a gait pattern that is more difficult to perform than that of level walking. This strenuous environment puts the lower limbs at a risk of falling. However, walking on sloped surfaces cannot be avoided because of the constructed or natural surroundings. An inline surface or slope can be considered as an environmental risk factor for walking. Therefore, maintaining balance is a crucial challenge in the postural control system during ablution.

Incline walking can be characterized by peak propulsive and braking forces [1–5]. An individual on an inclined plane experiences gravitational force vectors, which are normal and parallel forces. Braking and propulsive forces are terms used to describe the parallel forces. Balance loss or falls that might cause the development of injuries have a significant connection to the propelling and braking forces that occur during inclined walking [6]. Various measurement methods have been used to investigate balance performance and stability, such as the required coefficient of friction (RCOF), postural stability index (PSI), and center-of-pressure–center-of-mass (COP-COM) distance. The derivation of these measurements is typically based on the ground reaction force (GRF).

The RCOF is defined as the difference between the horizontal and vertical ground reaction forces [7]. The risk of falling or slipping increases as the RCOF increases. The findings show that the stability with respect to the RCOF parameter is affected by the external torque [8] or load carried [9] during gait.

Furthermore, Wikstrom et al. introduced the PSI measure utilizing force plate data to overcome the shortcomings of existing measures, while maintaining each of its own benefits [10]. Based on previous studies on PSI measures, dynamic stability is affected by visual cognitive tasks [11], load bearing [12], foot muscle morphology [13], and injury [14].

In addition, the relationship between the COP and the body's COM, which establishes the percentage of anterior GRF, affects the direction of the ground reaction force (GRF) vector. Research on balance and stability usually benefits from quantification of the COM and COP displacements [15].

Previous studies have shown that surface inclination decreases gait stability [16] and has a greater fall risk than stair walking [17]. In addition, the surface inclination also affects the gait characteristics and ground reaction force [18], which influence the slip potential or fall. In a previous study investigating the joint contact force during slope walking, it was reported that the ankle contact force increased with an increase in surface inclination [19,20]. In general, both postural stability and loading response seem to affect surface inclination, as slope walking has different challenges to level walking. Understanding the relationship between stability and lower-extremity joint reaction forces (JRFs) contributes to a broader field of biomechanics and human movement analysis, and can be utilized to determine factors that contribute to the risks of slips, trips, and falls during slope walking. However, how the response of lower-extremity joint reaction forces, due to changes in surface inclination angles during slope walking, could influence body stability remains unclear.

Thus, this study aimed to assess the relationship between stability parameters and lower-extremity JRFs during inclined and declined walking. The findings can be used to gain a deeper understanding of musculoskeletal system adaptation to slope walking, as well as to design interventions and safety measures to prevent injuries during navigation. The outcomes could also be set as a theoretical basis for selecting a suitable method of measurement to explore and understand the injury risk related to stability and load bearing during inclined walking.

2. Materials and Methods

2.1. Experimental Protocol

Twenty male subjects with no lower-extremity injuries, prior musculoskeletal injuries, or orthopedic abnormalities volunteered, with a mean age of 24 ± 1.2 years, height of 172 ± 2.7 cm, and body mass of 67 ± 6.7 kg (normal body mass index (BMI) category). The subjects were informed and provided written consent prior to participating, in accordance with a protocol approved by the Ethics Committee of Universiti Malaysia Perlis. The subjects were then allowed to walk on a customized inclined platform to familiarize themselves with each experimental condition, as depicted in Figure 1. The custom-built wooden slope platform had a flexible angle feature to be adjusted. The slope was 5 m long with a 1 m broad walkway. Two force plates (Bertec Corporation, Columbus, OH, USA) with dimensions of 60 cm × 40 cm × 10 cm were embedded under the walking platform at a frequency of 200 Hz. Five Oqus cameras in a motion-capture system (Qualysis, Gothenburg, Sweden) at a frequency of 200 Hz were used to obtain three-dimensional (3D) dynamic and static data. Ten reflective markers with a diameter of 20 mm wrapped with reflective tape were attached to the subjects using a revised form of the "Plug-in Gait" lower limb marker set, as shown in Figure 2. The subjects were instructed to walk along the platform through the force plate at their convenient walking speed without changing their steps to mimic normal walking style while wearing minimally shoes on a level and on three different incline platforms with angles of 5°, 7.5°, and 10° both upward and downward after the static position was recorded (Figure 3).

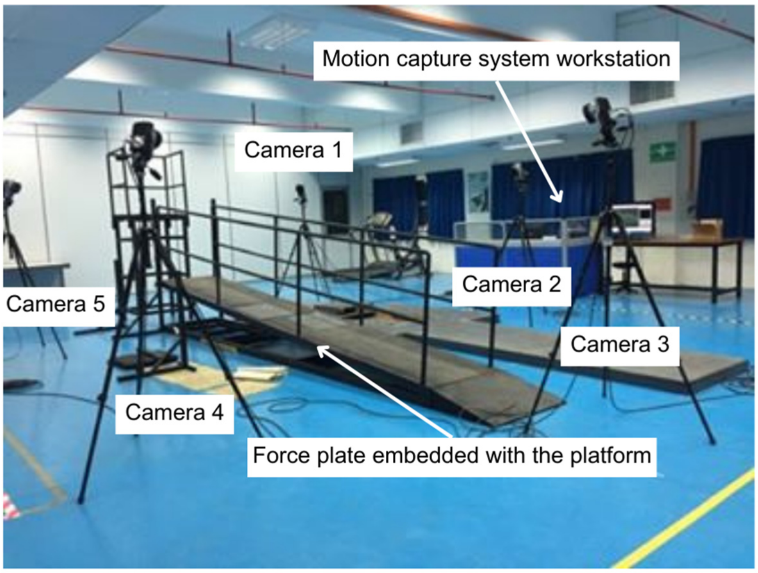

Figure 1. Equipment set-up.

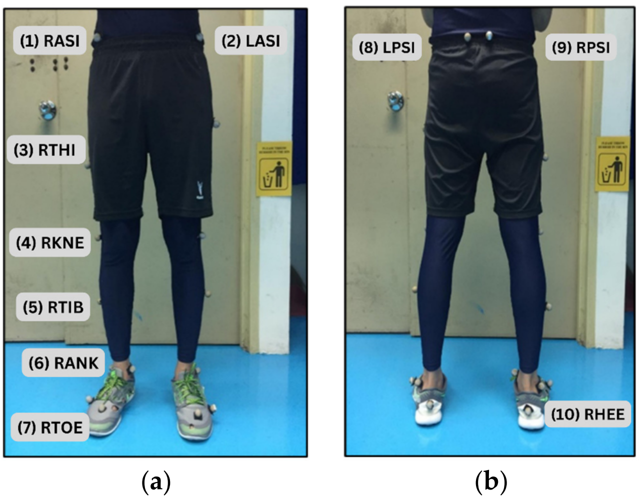

Figure 2. Marker placement on the participant's body: (**a**) anterior view, (**b**) posterior view.

Figure 3. Illustration of subject walking downward on the customized slope platform.

2.2. Measured Parameters

The parameters assessed and studied were (1) the ground reaction force (GRF), (2) the JRF of the lower limb (hip, knee, and ankle) (the force exerted at each lower limb joint with respect to the anatomical coordinate system plane), (3) the center of mass (COM), and (4) the center of pressure (COP).

Static and dynamic data (GRF, COM, and COP) were obtained using a motion-capture system. The data were then exported to Visual 3D C-Motion software (3.91.0) and converted into a 3.cd format file for the filtering process. Low-pass filters were used to filter the data at a cutoff frequency of 6 Hz. The model was then constructed using the Visual 3D C-motion software, as shown in Figure 4. The Visual 3D hybrid model creates a static model comprising four segments: the pelvis, thigh, shank, and foot. The input data of the subject's height and weight were required to obtain the mass volume of the body. The JRF for each joint of the lower limb (Figure 5) was acquired after the static model was assigned to the motion file and model-based data were computed. All data were normalized to body mass.

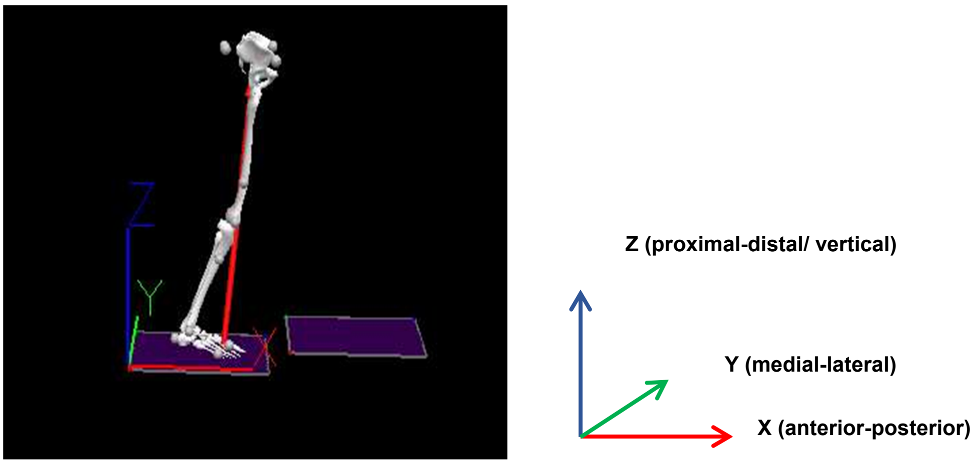

Figure 4. Segmental model during incline walking (using Visual 3D C-motion software).

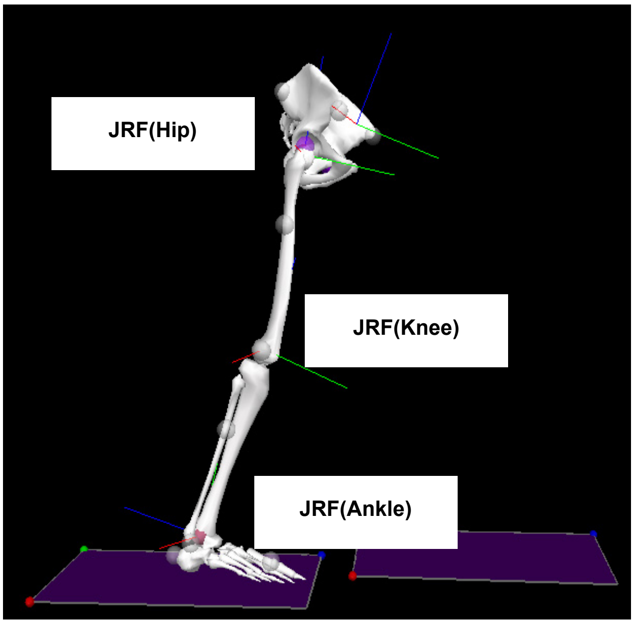

Figure 5. Location of the JRF of the lower limb.

2.2.1. Required Coefficient of Friction (RCOF)

The RCOF can be defined as the minimal coefficient of friction required to avoid the initiation of slippage during foot contact. The RCOF can be mathematically expressed as in Equation (1):

$$\mathrm{RCOF} = \frac{\sqrt{(\mathrm{F_{AP}}^2 + \mathrm{F_{ML}}^2)}}{\mathrm{F_V}} \quad (1)$$

where

$\mathrm{F_{AP}}$ = GRF in anterior − posterior direction
$\mathrm{F_{ML}}$ = GRF in medial − lateral direction
$\mathrm{F_V}$ = vertical GRF

2.2.2. Postural Stability Index (PSI)

According to Wikstrom et al. [10], the PSI involves the calculation of the stability index (SI) in three main directions (anterior–posterior (AP), medial–lateral (ML), and vertical (V)). These indices evaluate movements around a zero point along the frame using the mean square deviations from the GRF data in each direction. These parameters are described using the relationships listed in Table 1.

Table 1. Equations for the calculation of the APSI, MLSI, and VSI.

Variable	Equation	
APSI	$= \sqrt{\frac{\sum(0-\mathrm{GRFx})^2}{\text{num of frame}} \div \mathrm{BW}\,^*}$	(2)
MLSI	$= \sqrt{\frac{\sum(0-\mathrm{GRFy})^2}{\text{num of frame}} \div \mathrm{BW}\,^*}$	(3)
VSI	$= \sqrt{\frac{\sum(\text{Body weight}-\mathrm{GRFz})^2}{\text{num of frame}} \div \mathrm{BW}\,^*}$	(4)

* BW = body weight.

2.2.3. Center of Pressure–Center of Mass (COP-COM) Distance

The kinematic COP and COM trajectories in terms of the COP-COM distance were merged to form a balance measure. The COP was evaluated using Visual 3D software

(3.91.0), and COM was determined using the sacral position [21]. Both the COP and COM can be formulated using the following equations for the AP and ML directions:

$$COP = \frac{COP_{max} - COP_{min}}{l_0} \quad (5)$$

$$COM = \frac{COM_{max} - COM_{min}}{l_0} \quad (6)$$

where

COP_{max} = the maximum mean COP displacement
COP_{min} = the minimum mean COP displacement
COM_{max} = the maximum mean COM displacement
COM_{min} = the minimum mean COM displacement
l_0 = original leg length

The COP-COM distance of the COP and COM displacement in the anterior–posterior (AP) and medial–lateral (ML) directions were computed using the following equations:

$$COP - COM\ distance_{AP} = RMS|COP - COM_{AP}| \quad (7)$$

$$COP - COM\ distance_{ML} = RMS|COP - COM_{ML}| \quad (8)$$

where

COM_{AP} = center of mass (anterior − posterior direction)
COM_{ML} = center of mass (medial − lateral direction)

2.3. Statistical Analysis

Statistical analyses were performed using Statistical Package for the Social Sciences (SPSS) Version 26.0 (IBM, Armonk, NY, USA) software. Correlation analysis was performed between the RCOF during peak GRF and initial foot contact and the resultant JRFs at the lower-extremity joints (i.e., hip, knee, and ankle). Correlation analysis was also performed between the PSI and JRFs at the lower-extremity joints in all directions (anterior–posterior, medial–lateral, and proximal–distal) and between the COP-COM distance and JRFs at all lower-extremity joints in both directions (anterior–posterior and medial–lateral). To evaluate the stability parameter response during slope walking in comparison to level walking, the non-parametric Kruskal–Wallis test was performed using the mean value after the Shapiro–Wilk normality test was completed. The Pearson correlation coefficient was calculated to quantify the relationship between stability parameters (the PSI, RCOF, and COP-COM distance) and the JRF during incline and decline walking. Statistical significance was set at $p < 0.05$. The correlation coefficient was expressed as r and determines the strength and direction of the relationship between the two variables investigated, which were scaled within ranges from −1 to +1. When r = 0, there is no linear relationship between the variables, and as the value of r increases and eventually becomes a straight line approaching −1 or +1, the relationship becomes stronger, either negatively or positively [16].

3. Results

3.1. RCOF during Level and Slope Walking

The RCOF was identified during the initial foot contact and peak GRF. As shown in Figure 6, the RCOF during the initial foot contact was found to be insensitive to inclination ($p > 0.05$) when walking on an incline. Meanwhile, during declined walking, the subjects showed the possibility of slipping at 7.5° as the RCOF started to increase significantly ($p < 0.05$) compared to level walking.

In contrast, the RCOF at peak GRF during inclined walking started to increase ($p < 0.05$) at 7.5° to 10° inclination but was unaffected during declined walking, as no significant differences were observed ($p > 0.05$). The increment in the RCOF during these inclinations in comparison to the level surface suggests the probability of slips during slope walking at certain sloped angles (Figure 7).

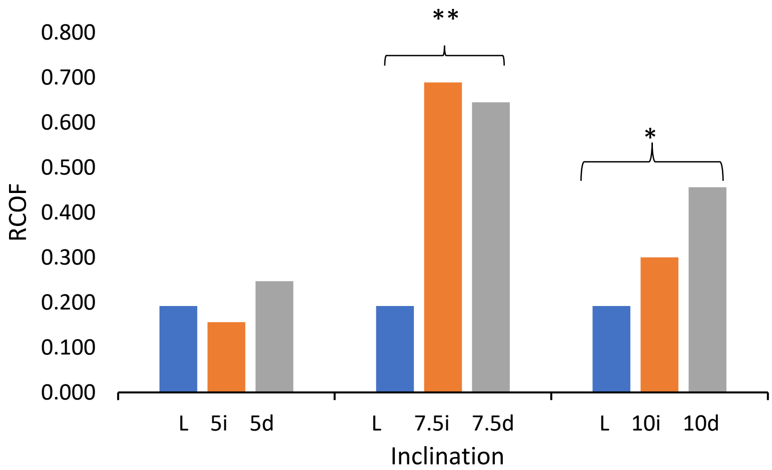

Figure 6. Comparison of the RCOF between level and slope walking during initial contact. Note: L = level walking; 5i, 7.5i, 10i = inclined walking of 5°, 7.5°, 10°; 5d, 7.5d, 10d = declined walking of 5°, 7.5°, 10°; * = significant difference between level and inclined walking; ** = significant difference compared between level and declined walking.

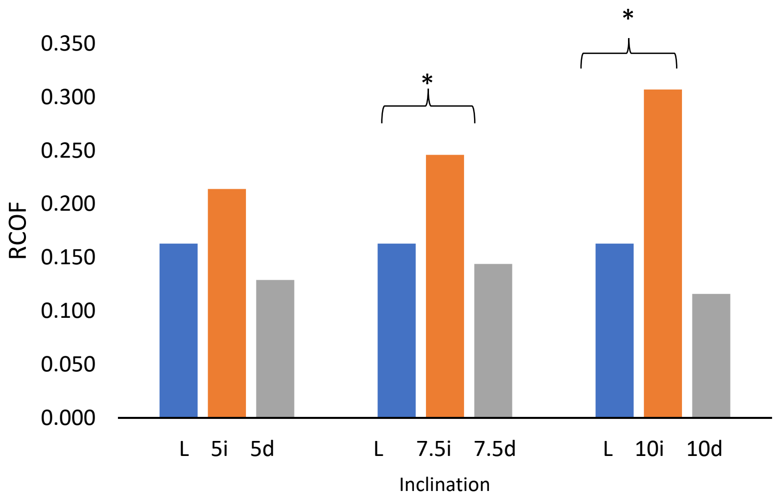

Figure 7. Comparison of the RCOF between level and slope walking during peak GRF. Note: L = level walking; 5i, 7.5i, 10i = inclined walking of 5°, 7.5°, 10°; 5d, 7.5d, 10d = decline walking of 5°, 7.5°, 10°; * = significant difference compared between level and inclined walking.

3.2. Postural Stability Index during Level and Slope Walking

As shown in Figure 8, the PSI in the anterior–posterior direction during slope walking in comparison to level walking began to increase at an inclination of 5°–10°, with a statistically significant difference ($p < 0.05$).

Meanwhile, the PSI in the medial–lateral direction in comparison to level walking only started to increase with a statistically significant difference at 10° inclination during inclined walking compared to 5°–7.5° inclination during declined walking.

The PSI in the proximal–distal direction was found to be unaffected by inclination during inclined walking; instead, it began to demonstrate a higher possibility of falling at 7.5°–10° inclination during declined walking.

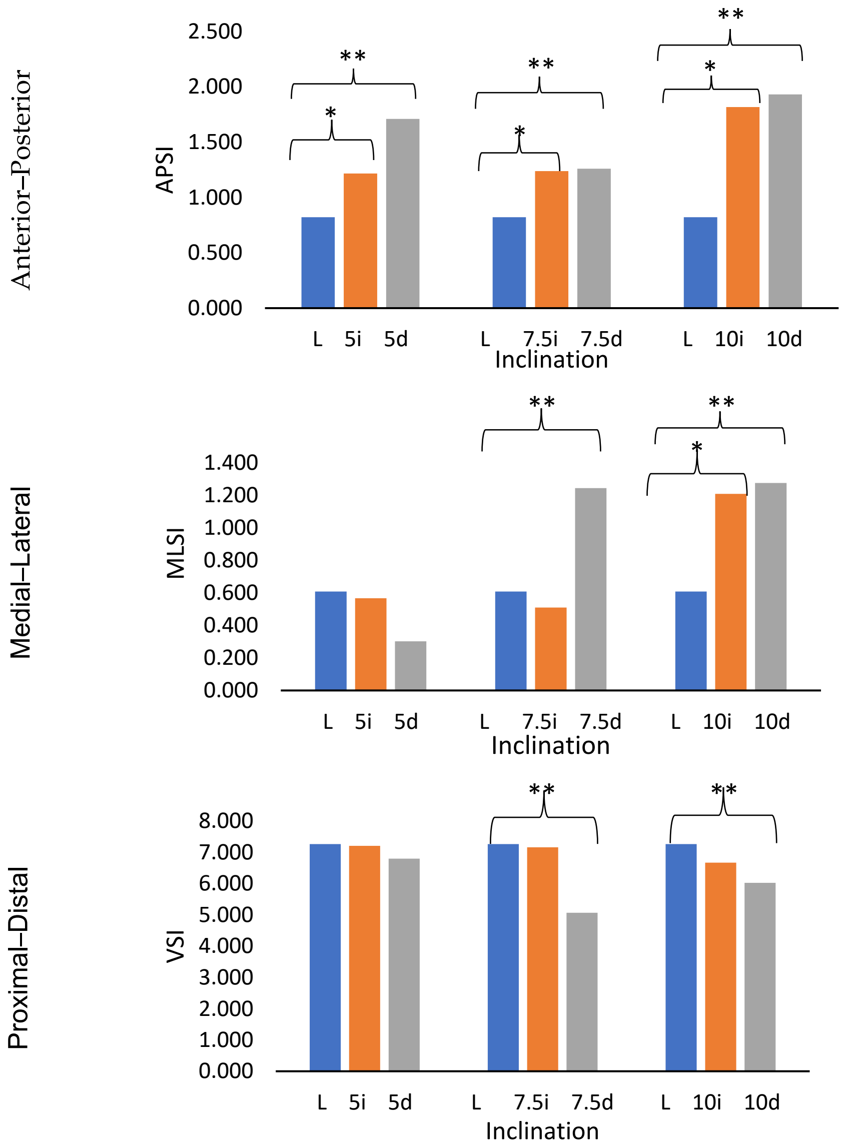

Figure 8. Comparison of the PSI between level and slope walking. Note: L = level walking; 5i, 7.5i, 10i = inclined walking of 5°, 7.5°, 10°; 5d, 7.5d, 10d = decline walking of 5°, 7.5°, 10°; * = significant difference in comparison between level and inclined walking; ** = significant difference compared between level and declined walking.

3.3. COP-COM Distance during Level and Slope Walking

As shown in Figure 9, the COP-COM distance in the anterior–posterior direction started to increase at 7.5° toward a 10° inclination, with a significant value of $p < 0.05$ during incline walking. Meanwhile, a statistically significant difference ($p < 0.05$) was found between declined and level walking, suggesting that the COP-COM distance in the anterior–posterior direction was affected by surface inclination, even at a 5° inclination.

On the other hand, the COP–COM distance in the medial–lateral direction only started to have a tendency for greater postural control at a 10° inclination for both inclined and declined walking ($p < 0.05$).

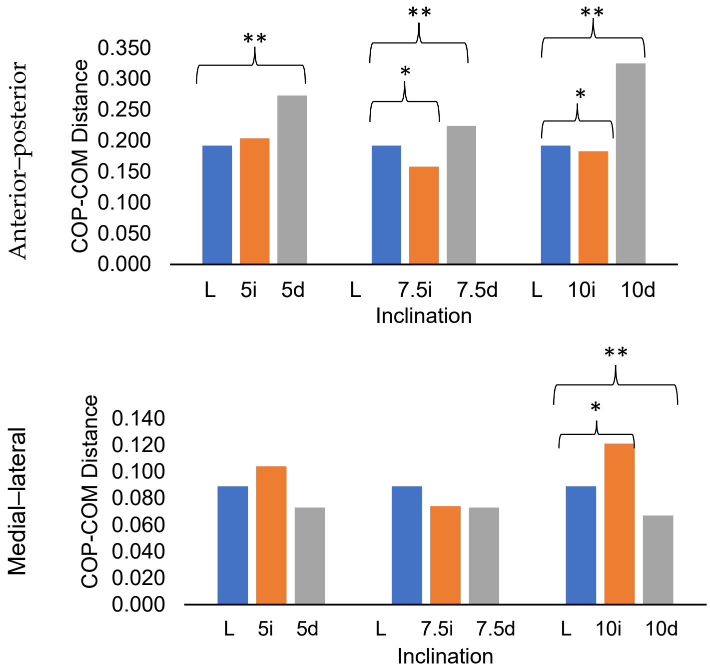

Figure 9. Comparison of the COP-COM distance between level and slope walking. Note: L = level walking; 5i, 7.5i, 10i = inclined walking of 5°, 7.5°, 10°; 5d, 7.5d, 10d = decline walking of 5°, 7.5°, 10°; * = significant difference between level and inclined walking; ** = significant difference between level and declined walking.

3.4. Relationship between the RCOF (Initial Foot Contact) and the JRF during Slope Walking

The results of the correlation analysis between the RCOF during the initial foot contact of the stance phase and the JRF of the lower-extremity joints during inclined and declined walking are shown in Figure 10. The results show a non-significant correlation between the RCOF and JRF at the ankle and knee during inclined walking (r = −0.341 and −0.336, respectively). The RCOF was significantly correlated with the JRF at the hip (r = −0.403; $p < 0.05$). During declined walking, similar findings were found, in that the RCOF was significantly correlated with the JRF at the ankle, knee, and hip (r = −0.449, −0.488, and −0.446; $p < 0.05$).

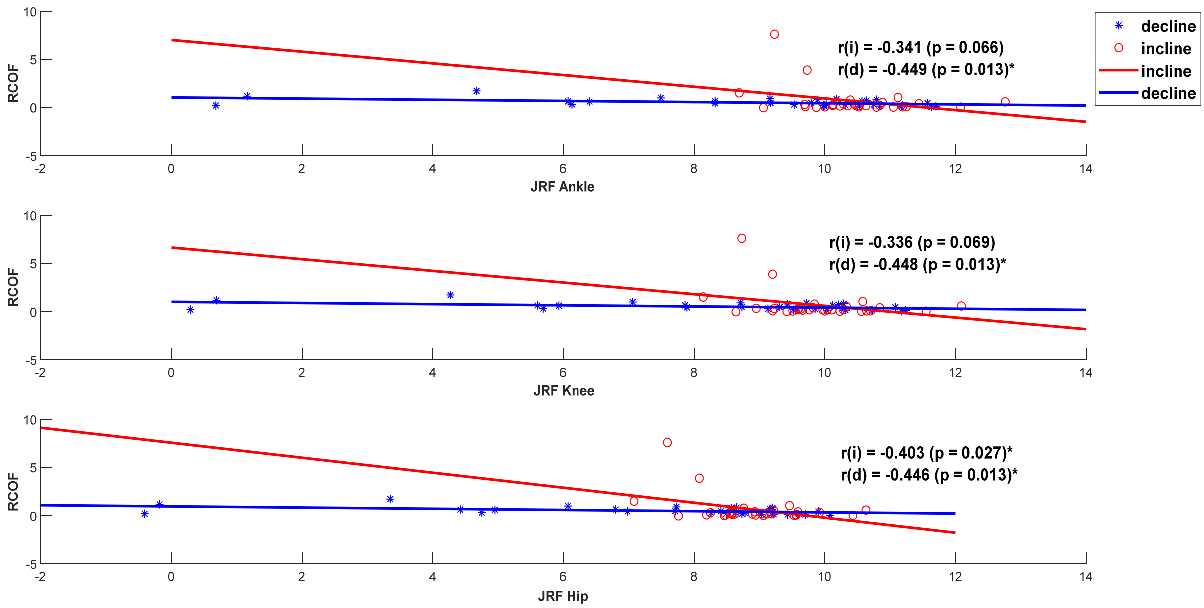

Figure 10. Relationship between the RCOF (initial foot strike) and the JRF of the lower limb during slope walking. * Significant different at $p < 0.05$.

3.5. Relationship between the RCOF (Peak GRF) and the JRF during Inclined and Declined Walking

During inclined walking, as presented in Figure 11, the results show that the RCOF during the peak GRF was not significantly correlated with the JRF at the ankle, knee, or hip (r = −0.086, 0.034, and −0.207, respectively), and the results also indicate a non-significant correlation between the RCOF and JRF at the ankle, knee, and hip (r = 0.112, 0.111, and 0.115, respectively) during declined walking.

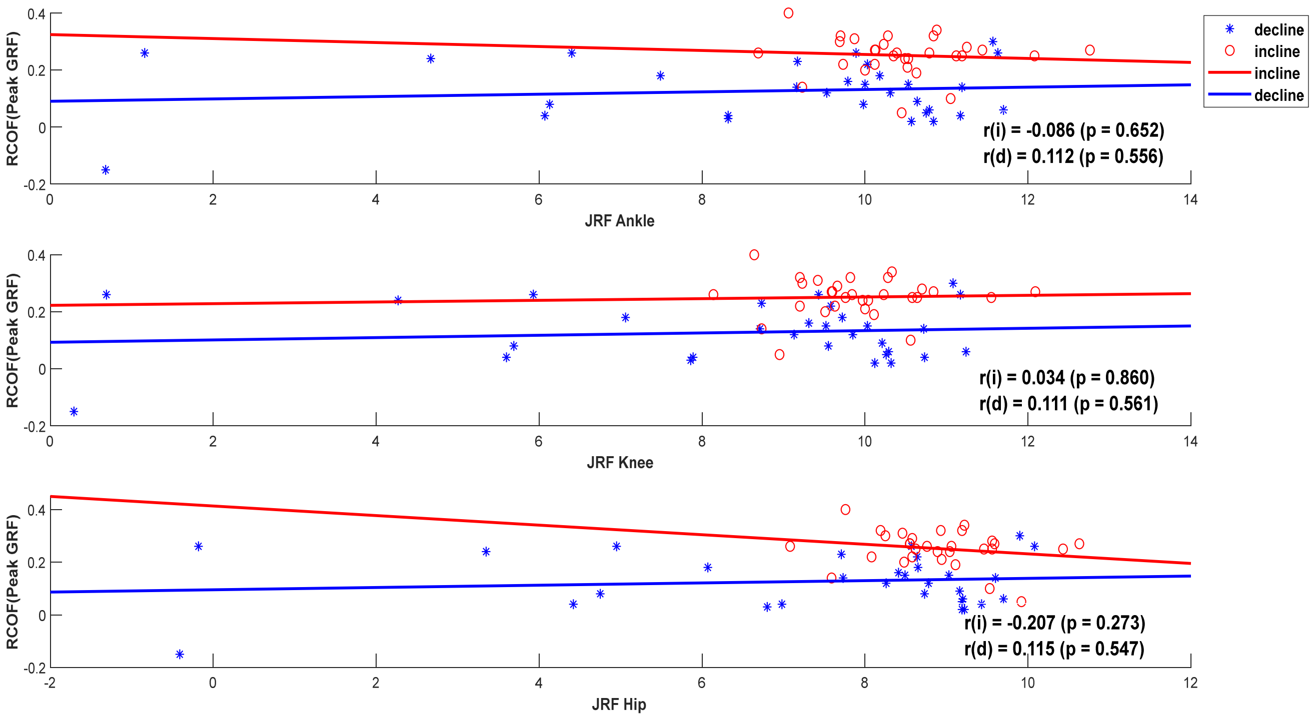

Figure 11. Relationship between the RCOF (peak GRF) and the JRF of the lower limb during slope walking.

3.6. Relationship between the PSI and JRF during Inclined and Declined Walking

As shown in Figure 12, the PSI in the anterior–posterior direction (APSI) was not significantly correlated with the JRF at the ankle, knee, or hip during inclined walking (r = 0.021, 0.282, and 0.238). Similarly, a non-significant correlation was found between the APSI and JRF of the ankle, knee, and hip (r = 0.076, −0.427, and −0.562, respectively) during declined walking.

Meanwhile, as can be seen in Figure 13, the PSI in the medial–lateral direction (MLSI) was found to positively correlate with the JRF at the knee (r = 0.380, $p < 0.05$) but was not significantly correlated with the JRF at the ankle or hip (r = 0.186 and 0.248, respectively) during inclined walking. During declined walking, the MLSI was found to be negatively correlated with the JRF at the hip (r = −0.365, $p < 0.05$) but was not significantly correlated with the JRF at the ankle or knee (r= −0.073 and 0.018, respectively).

Furthermore, the findings showed that the PSI in the proximal–distal direction (VSI) was positively correlated with the JRF at the ankle, knee, and hip (r = 0.734, 0.769, and 0.720, respectively; $p < 0.05$) during inclined walking. Similarly, there was a positive correlation between the VSI and JRF at the ankle, knee, and hip (r = 0.931, 0.926, and 0.936, respectively; $p < 0.05$) during declined walking (Figure 14).

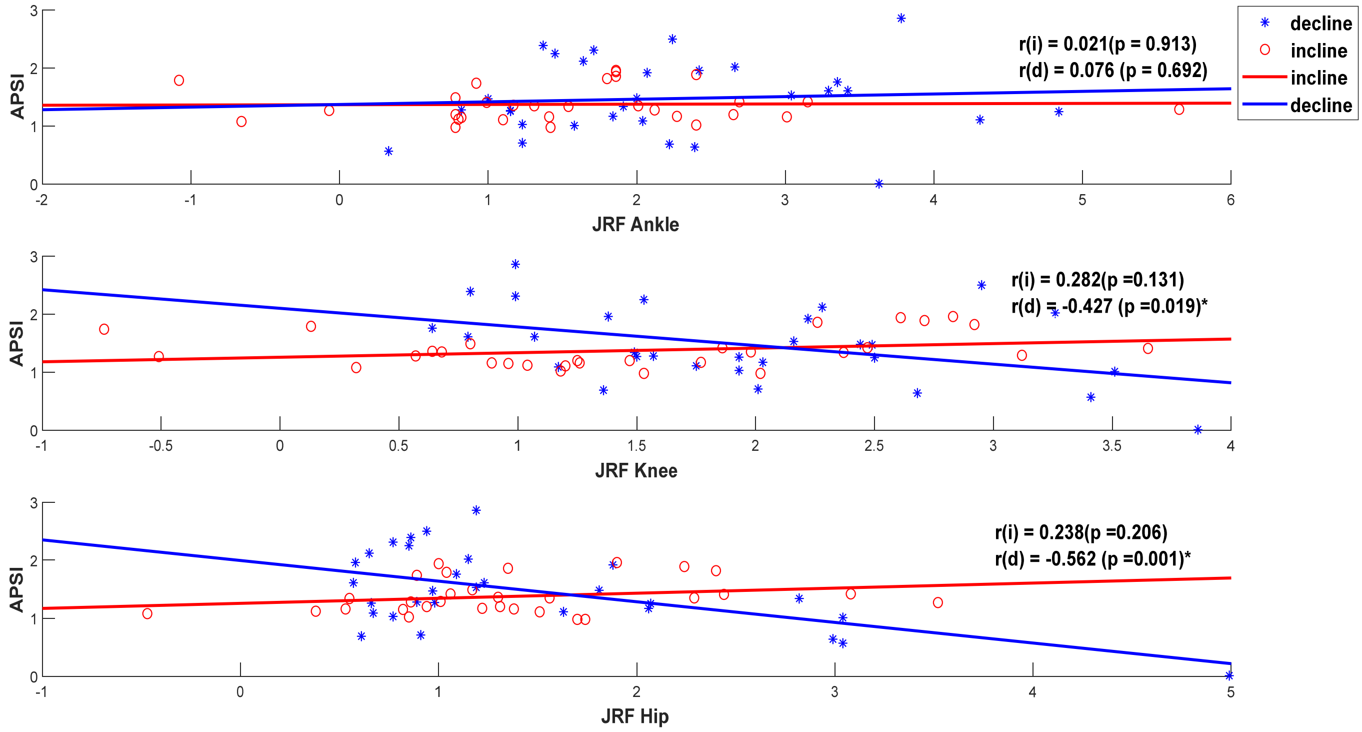

Figure 12. Relationship between the APSI and JRF of the lower limb during slope walking. * Significant different at $p < 0.05$.

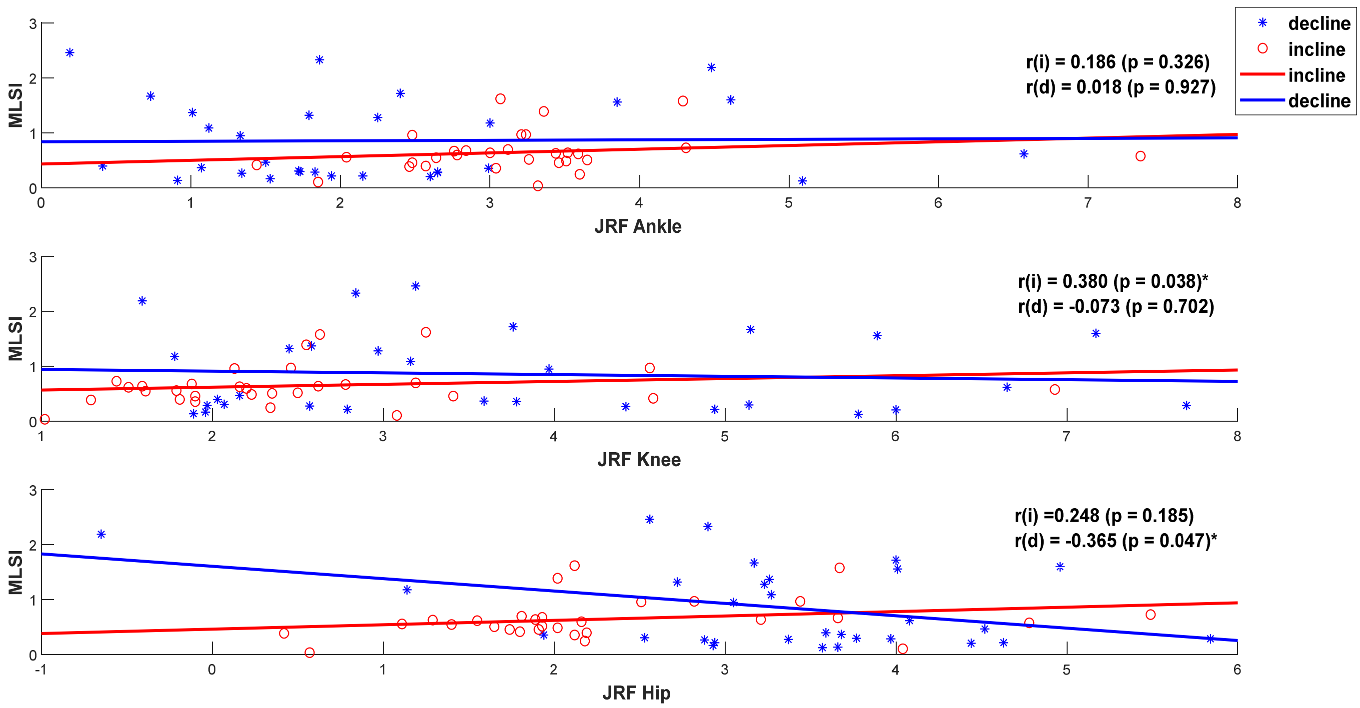

Figure 13. Relationship between the MLSI and JRF of the lower limb during slope walking. * Significant different at $p < 0.05$.

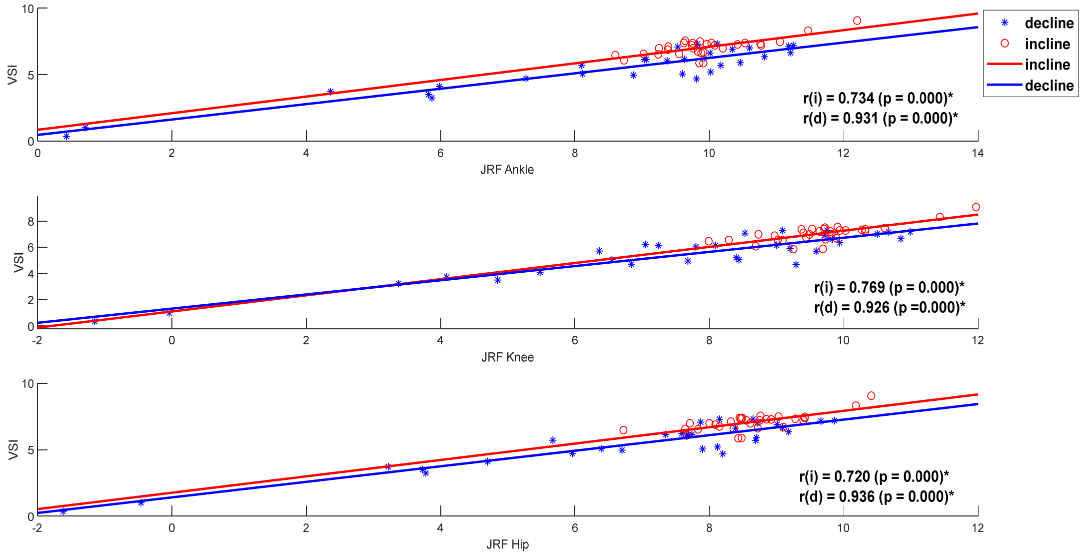

Figure 14. Relationship between the VSI and JRF of the lower limb during slope walking. * Significant different at $p < 0.05$.

3.7. Relationship between the COP-COM Distance and JRF during Slope Walking

Figure 15 shows the correlation analysis results between the COP-COM distance and JRFs at all lower-extremity joints during slope walking. It was found that the COP-COM distance in the anterior–posterior direction was positively correlated with the JRF at the knee (r = 0.505, $p < 0.05$) but not significantly correlated with the JRF at the ankle or hip (r = 0.270 and 0.301, respectively) during inclined walking. During declined walking, there was no significant correlation between the COP-COM distance in the anterior–posterior direction and the JRF at the ankle, knee, or hip (r = 0.328, −0.219, and −0.312, respectively).

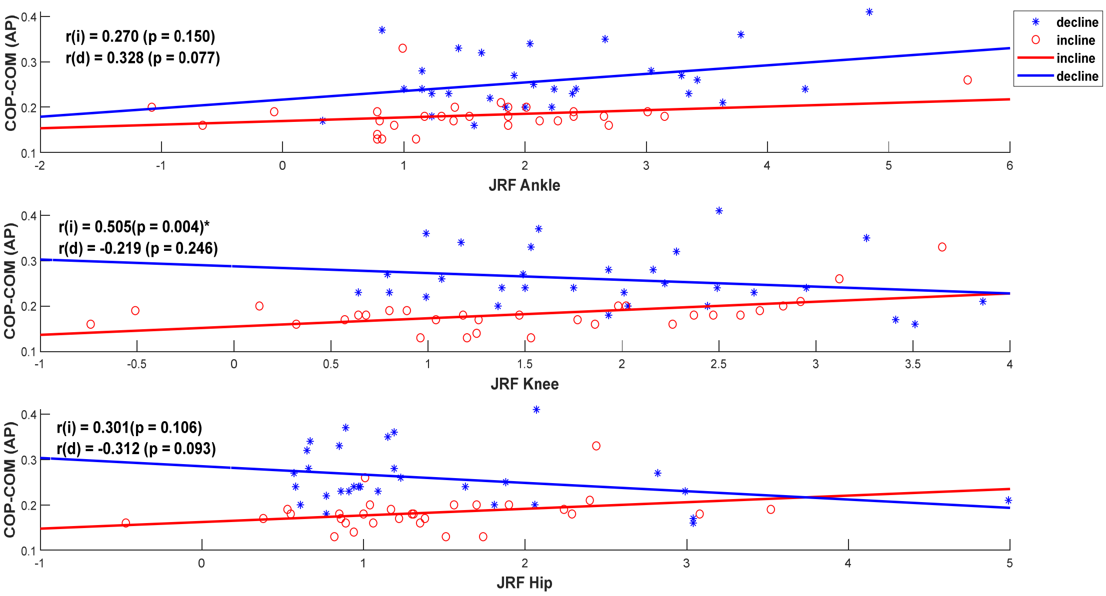

Figure 15. Relationship between the COP-COM distance (anterior–posterior) and the JRF of the lower limb during slope walking. * Significant different at $p < 0.05$.

The COP-COM distance in the medial–lateral direction was not significantly correlated with the JRF at the ankle, knee, or hip during inclined walking (r = 0.309, 0.243, and 0.281, respectively) (Figure 16). Meanwhile, during declined walking, the COP-COM distance in the medial–lateral direction was not significantly correlated with the JRF at the ankle or knee (r = 0.266 and 0.004, respectively) but was positively correlated with the JRF at the hip (r = 0.342, $p < 0.05$).

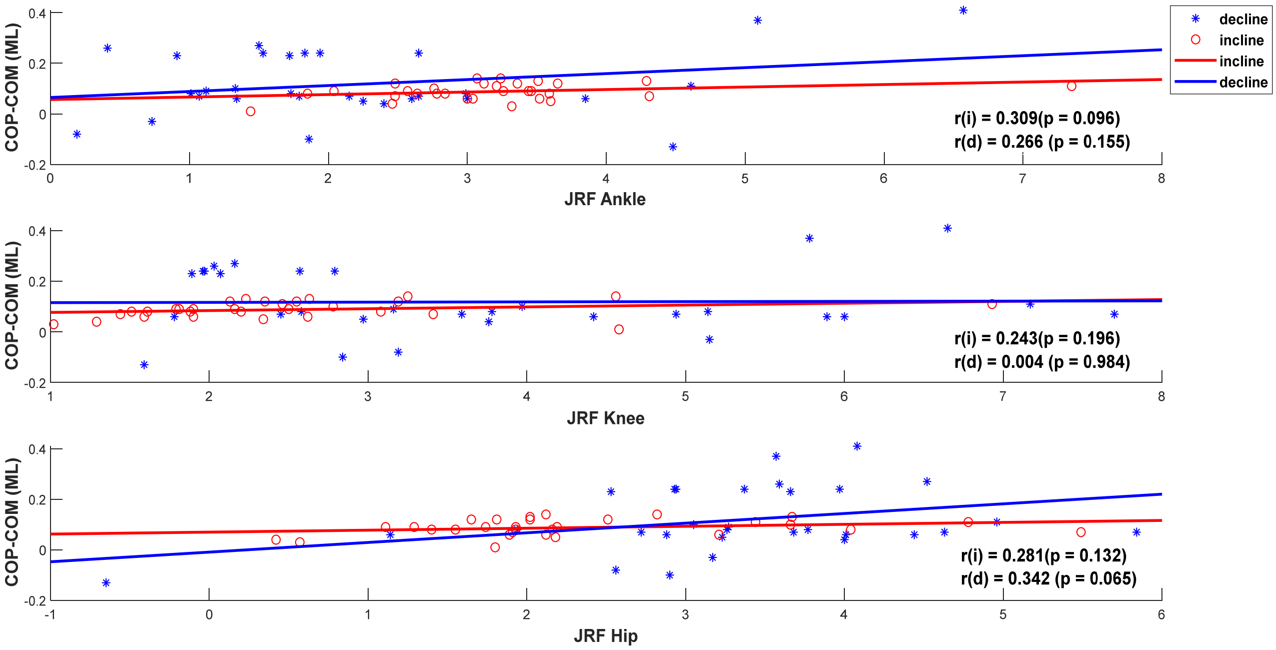

Figure 16. Relationship between the COP-COM distance (medial–lateral) and the JRF of the lower limb during slope walking.

4. Discussions

This study aimed to investigate the relationship between body stability and loading response parameters when walking on inclined and declined surfaces. The association of stability parameters in terms of the RCOF, PSI, and COP-COM distance with the JRF as a loading response was studied based on correlation analysis.

4.1. The Relationship between the RCOF and JRF of the Lower Extremity during Level and Slope Walking

The findings of this study on the RCOF at initial foot contact during decline walking indicate an increment that began at a 7.5°–10° incline compared to level walking, with a statistically significant difference (Figure 5). It seems possible that these results may be attributed to the normal curve of the RCOF having the two highest points and the lowest point with larger shear forces. The peak occurred during the initial contact and push-off phases [22]. In contrast, it was found that the RCOF at peak GRF during inclined walking started to increase at a 7.5°–10° inclination compared to level walking, with a statistically significant difference (Figure 6). These results are consistent with previous studies that reported that the RCOF is affected at the end of the stance phase of the gait cycle, where the GRF is at its maximum [23].

Based on the correlation analysis between the RCOF during initial contact and the JRFs of all lower-extremity joints during inclined and declined walking, the results indicated that there was a negative correlation between these two parameters that was weak during inclined walking and moderate during declined walking (Figure 9). In other words, the JRFs of all lower-extremity joints changed in the opposite direction to that of the RCOF. As the RCOF increases, the possibility of falling increases, as a high friction demand indicates that the surface has no or less grip ability [24]. The results show that as the RCOF increased, the JRFs at all lower-extremity joints decreased and vice versa. Therefore, a possible explanation for the findings of the correlation analysis between the JRFs and RCOF is that during the initial contact of the foot with the ground, the JRFs at all lower limbs that are associated with the GRF are in a high state, as it is a short-period phase, which is the start of the loading response or weight acceptance and the beginning of the stance phase [25]. As the foot slightly touches the ground, the friction demand decreases.

4.2. The Relationship between the PSI and JRF of the Lower Extremity during Level and Slope Walking

Another important finding in this study was that the PSI was shown to be most responsive in the anterior–posterior direction of surface inclination during slope walking (incline and decline), even at a minimum slope angle of 5° (Figure 7). Moreover, this study discovered that inclined surfaces began at 7.5° during inclined walking and even 5° during declined walking in the anterior–posterior direction, impacting the COP-COM distance in comparison with level walking (Figure 8). The antero-posterior direction pattern specifically focuses on balance in the front–back direction. Thus, the observed results for these two stability parameters could be due to slope walking involving walking on an inclined surface, which challenges postural stability owing to altered gravitational forces. To maintain stability and prevent falls, the body must counteract the force of gravity, which attracts and exerts and attracts it in opposing and corresponding directions while walking uphill or downhill, respectively [26].

In addition, the results of the correlation analysis between the PSI in the proximal–distal or vertical direction and the JRFs at all lower-extremity joints in this study reported that there was a significant strong positive correlation between these parameters during both inclined and declined walking (Figure 13). These findings suggest that the JRFs of all lower-extremity joints change in a direction similar to that of the PSI in the vertical direction. These results are likely related to the vertical GRF, which is the external force exerted during gait motion. The different GRF developed during sloped walking led to changes in the internal joint moment due to the activation of related muscles [1,27,28]. The GRF, which acts on the joint surface, produces a tensile force generated by muscle activation and contributes to joint load changes. The joint load was described by the JRF. Body weight, which is the force that determines the amount of GRF exerted, was included in the vertical PSI calculations. Therefore, changes in the vertical JRF dependent on the GRF will change the PSI in the vertical direction, which is dependent on body weight.

4.3. The Relationship between the COP-COM Distance and the JRF of the Lower Extremity during Level and Slope Walking

Furthermore, the findings of the correlation analysis between the COP-COM distance and JRFs at the lower-extremity joints showed weak and very positive correlations in the medial–lateral directions for slope walking (both inclined and declined) (Figure 15). The results indicate that the JRF of the lower-extremity joints increases and decreases in a manner similar to the COP-COM distance in the medial–lateral direction. These results are in accordance with recent studies indicating that during slope walking, the modification of constant horizontal forces produced a similar direction of limb modification that can be measured as COM dynamics [29]. These results on the relationship between JRF and COP-COM distance could be attributed to kinematic changes to adapt to the slope surface during walking. Changes in limb length and orientation, which determine the COP-COM distance, are related to kinematic patterns with slope modifications [30]. However, the JRF also changes in accordance with kinematic changes to adapt to the slope during walking. For example, a previous study reported that the JRF at the knee in the medio-lateral direction is responsive to changes in the slope angle during slope walking [31]. This result was possibly due to an increase in the maximum knee extension during inclined and declined walking [32]. The ideal bony weight-bearing support for the posture of the knee was due to the femoral condyles attached to the tibial condyles by the gliding actions of the knee as a hinge joint during knee extension [33]. In other words, the JRF responds to surface inclination owing to kinematic changes. Therefore, it is likely that such an association exists between the JRFs of all lower-extremity joints and the COP-COM distance during slope walking.

Therefore, in general, it was found that the correlation between the stability parameter measured and the loading response in terms of the JRF of the lower-extremity joints during slope walking is inconsistent among the stability parameters measured. The inconsistent relationship among the parameters measured might be because each stability parameter investigated in the current study involved different components of biomechanical measurement that resulted in different responses toward the JRF. Thus, different strengths and directions of correlation between the stability parameters and the JRF during slope walking were found. However, although the results were inconsistent, some significant findings from the correlation analysis were observed in this study. The results obtained from this study show that the RCOF during the initial foot strike, the PSI in the proximal–distal direction, and the COP-COM in the medial–lateral direction were consistent with the JRFs of all lower-extremity joints. Therefore, this study suggests that the use of a single measure is not always advocated, as each parameter may evaluate different elements that lead to different findings.

5. Conclusions

This study aimed to assess the correlation between stability parameters such as the RCOF, PSI, and COP-COM distance and loading response in terms of the JRF during slope walking (incline and decline). This study found that the JRF of the lower-extremity joints changes in opposition to the changes in the RCOF during the initial strike when incline and decline walking, with different strengths of correlation. This study also reported that the PSI and JRF in the proximal–distal direction has a strong and positive correlation, where the PSI is directly proportional to the JRF. In addition, the findings of this study show that, during slope walking, the JRF of the lower extremity also changed in a manner similar to the COP-COM distance in the medial–lateral direction. Taken together, these results suggest that each parameter of stability correlates with the JRF of lower-extremity joints as loading responses in different directions and of different strengths. Therefore, various stability measurement methods should be considered to understand the injury risk during slope walking, which is closely related to these factors.

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