Surface inclination effects on muscle and joint contact force during walking: A systematic review

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Abstract. Outdoor surfaces are generally uneven as the surface topography diverges in terms of its inclination. Due to variation of inclination, there are risks of injury caused by muscle response and force reaction during gait. The objective of this review is to characterize the effects of incline surface on muscle and forces during walking that contribute to injury. The search strategy was carried out from Worldcat.org database. Majority of the previous studies agree on the fact that muscle response and force significantly change according to the changes of surface inclination. Future studies involving ligament force should be performed in order to obtain a valid result on muscle response and force reaction during inclined gait.

1. Introduction

Outdoor surfaces are generally uneven as the surface topography diverge in terms of its inclination. The varies of unevenness is might be due to unavoidable human error in manmade work or consequence of the environmental in the case for ramps to access the building or pavement on hills respectively [1].

Muscle are the important component in the incline surface investigation and plays the key role in joint contact forces [2]. It has been reported that, a greater post-exercise muscle soreness and damage during downhill movement which resulting from the increase of muscle eccentric [3] may cause mechanical changes on lower limb posture that lead to future injury [4]. Furthermore, reaction force is reported to be correlated with running surface [5] and increase in lower extremity joint loading in increment of slope compared to level surface gait have been founded [6]. Accumulated high impact forces and joint loading lead to the early onset of fatigue [7], development of stress fractures [8] and patellofemoral pain in runners [9].

Whatever the origin, in order to prevent fall and injury, incline surface require a particular different demand compared to level surface. Therefore, the objective of this paper is to review and characterize the effects of incline surface on muscle and forces during walking that contribute to injury.

2. Method

2.1. Search engine

This review had been completed by performing electronics search in March 2019 involving a database WoldCat.org. The selected articles were limited for past ten years studies only that is from 2009 until 2019. The keyword for the search included ‘incline surface’, ‘slope’, ‘gait’, ‘muscle’ and ‘force’. A manual search on reference list of reviewed articles is completed to ensure no overlooked articles. The
articles in English only were individually selected by authors. Articles that met the following criteria were considered: (1) investigation on inclined surface gait, (2) muscle as dependent variable, and (3) force as dependent variable.

2.2. Review process
Based on eligibility criteria, the articles were first screened on the title and abstract. A full-text evaluation is performed if the title and abstract could not provide adequate information of the chosen articles. Re-screened process is also completed to avoid any overlooked information.

2.3. Data extraction
The information collected from the reviewed articles are related to the main research theme that is objective, method implement, independent and dependent variables, as well as findings of the research.

3. Result

3.1. Effect of incline surface on muscle
A considerable amount of literatures has been published on the effect of incline surface to muscle response. In overall, muscle responses to surface inclination during gait can be divided into six measurement; electromyography (EMG) signals, EMG amplitude, muscle timing, muscle geometry, muscle force and muscle efficiency as shown in Table 1.

Based on review done, EMG signals which displayed muscle activities was assessed by majority of the previous studies. All of the articles, monitored EMG signals using surface electrode application. Bavdek et al.[10] and Mohammadi and Phadke [11] applied the surface electrode according to SENIAM method, instead, other previous study does not mentioned method used. However, each of these articles has specific software or method applied in order to analyze and process the EMG signals. The software used are including Labchart 7 [10], LED-synchronized video [12], Biometric Ltd [11], and Delsys EMG works [13]. While, the method implemented in investigating EMG signals are such as telemetry system [14] and trapezoidal method [15]. In addition, musculoskeletal modelling and inverse dynamic was used to investigate muscle geometry and muscle force [2]. Other than that, Saito et al.[16] and Rozumalski et al.[17] extracted muscle synergies using non-negative matrix factorization (NMF).

In overall, by merging all findings of previous studies in this review, muscle activity is reported to be affected and influenced by surface inclination except for Slaughter et al. [13] who found no significant difference between these two variables. On the question of muscle response to incline surface, Kwee-Meier et al. [12] highlighted that peak activities of lower limb are age-related especially for m. gastrocnemius medialis (GAS) and m. soleus (SOL) in incline walking. Furthermore, foot strike pattern and leg dominancy of an individual should be considered to obtain an optimum prescription of walking as both influenced the muscle activity as reported by Ohira et al. [14] and Mohammadi & Phadke [11] respectively. Another important finding was that, muscle synergies extracted from lower limb were consistent in response to different slope and speed of walking [16], [17].

| No | Author | Objective | Independent variable | Dependent variable | Method used | Findings |
|----|--------|-----------|----------------------|--------------------|-------------|----------|
| 1  | Kwee-Meier et al.[9] | To investigate the muscle activation when walking on sloped surface among young and older adult. | Surface inclination 0°, 7°, and 14° | EMG – muscle activity signals | LED-synchronised video stream - analyses EMG signal | Peak activities of GAS and SOL are more restricted in older adult compared to young adult. They compensate these limitations by ‘pull’ themselves instead of pushing during uphill walking |
| No | Author                        | Objective                                                                 | Independent variable                                      | Dependent variable                                      | Method used                                                                 | Findings                                                                                   |
|----|-------------------------------|---------------------------------------------------------------------------|------------------------------------------------------------|----------------------------------------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| 2  | Bavdek et al.[8]              | To study the characteristic of peroneal muscles during walking with different style. | Walking types: Flat surface (NORM) Medial incline ramp with a 30° inversion (FULL) - cross-slope walking | EMG – muscle activity signals Kinematic parameters *gait speed *stride length *contact time *foot position | Surface electrode; according to SENIAM method Labchart 7 – process EMG signal Stalker’s type hyper-frequency radar – measure gait speed | Peroneal muscle was affected during incline or ramp walking. Incline walking possibly implement as a strengthening peroneal muscle exercise. |
| 3  | Saito, Tomita, Ando, Watanabe, & Akima [15] | To assess the muscle synergies of lower limb during level and uphill treadmill walking. | Surface inclination 0% and 10% grade of treadmill Walking speed 60, 80, and 100 m/min | EMG – muscle activity signals | Surface electrode Non-negative matrix factorization (NNMF) – muscle synergies extraction | The muscle synergies extracted from lower limb showed a consistent pattern during walking on different inclination and speed. |
| 4  | Mohammadi & Phadke [11]      | To study the effects of incline surface and walking speed to ankle muscle activity among middle-age individual. | Surface inclination 0°, 3°, and 6° Walking speed self-selected self-selected +20% self-selected +40% | EMG amplitude Muscle co-contraction Muscle timing | Surface electrode; according to SENIAM method Biometrics Ltd software – EMG processing and analysis | Muscle in dominant leg showed a bias activity compared to the non-dominant leg might be due to age-related adaptation to overcome challenging walking. |
| 5  | Rozumalski, Steele, & Schwartz, [14] | To investigate the relation of synergies and gait changes during treadmill walking with different inclinations and speeds in developing children. | Surface inclination and walking speed combination speed: free speed, 110% of free speed, 120% free speed Slope:0°, 6°, 12° | EMG – muscle activity signals Kinematics data | Custom software (Matlab) – Ground reaction force collection Surface electrode NNMF – muscle synergies & synergies activation | The muscle synergies remain unchanged in response to changing of biomechanical task constraint show that neuromuscular control strategies do not change. The significant different shown in kinematics and kinetics data indicate different in movement pattern |
| No | Author | Objective | Independent variable | Dependent variable | Method used | Findings |
|----|--------|-----------|----------------------|-------------------|-------------|----------|
| 6  | Alexander & Schwameder, [2] | To study muscle force of lower limb during different inclination walking using musculoskeletal model. | Surface inclination (0°, ±6°, ±12° & 18°) | Mass Moment of inertia Muscle sites/geomet ry Muscle forces | AnyBody Modelling System (musculoskeletal model) Inverse dynamics | Lower limb muscle forces during incline compared to level walk were significantly changed except for Gluteus Medius muscle force. |
| 7  | Ortega & Farley[16] | To study the relation of metabolic cost, muscular efficiency and leg muscle co-activation of young and older person during level and uphill walking. | Surface inclination | METabolic cost Muscular efficiency Leg muscle activation | Rates of oxygen consumption & carbon dioxide production = indirect calorimetry surface EMG signals | Metabolic cost during uphill walking was increased due to increment of leg muscle co-activation and decrement of muscular efficiency among older adult but are unrelated to one another. |
| 8  | Ohira et al.,[12] | To study the response of leg muscle during walking on treadmill with different speed and inclination. | Surface inclination 0%, 6%, 10% and 15% Walking speed Foot strike pattern | EMG – muscle activity Kinematics data – knee and ankle angle Time spent for each step | Bipolar surface electrode – monitor muscle activity Telemetry system | To obtain an optimum prescription walking that associated with speed and inclination, the foot strike pattern of an individual should be considered. |
| 9  | Silder, Besier, & Delp[17] | To investigate muscle activation patterns, physical criteria and gait characteristic that best estimate metabolic cost during incline walking. | Surface inclination (0°, 5°, 10°) | Kinematic data (marker data) Ground reaction force Moments EMG signal (muscle activity) Joint work | Whole body dual-energy x-ray absorptiometry Surface electrode – monitor muscle activity | Metabolic cost during incline walking can be estimated based on muscle activities and biomechanical gait patterns for healthy adults walking with flexed knees, carrying loads at various speed. |
| 10 | Slaughter et al.[11] | To study the EMG activity of lower extremity skeletal muscle at knee and rotational differences between the leg and thigh during walking on different surfaces. | Surface condition Side-slope (5°, 10°) Incline treadmill (10°) Flat (0°) Ascended stairs | EMG signal Maximum voluntary contraction (MVC) Acceleration , rotation & magnetic field data – IMU device Angular velocity | Surface electrode – monitor muscle activity Delsys EMGworks program - analysis | There is little difference in knee joint loading when rotation about vertical axis and EMG activity was considered. |
3.2. Effect of incline surface on joint contact force (JCF)

Based on literature reviewed for past ten years, only two articles analyze JCF in investigating the surface inclination [3], [6]. Park et al.[3] compare the JCF during moderate and steep downhill running with level running. While, Alexander & Schwameder (2016) investigate JCF during walking at different slope.

As shown in Table 2, both articles have different approach in assessing the JCF. Park et al.[3] generally mentioned that inverse dynamics were performed to calculate joint force and moment. Instead of that, Alexander & Schwameder [6] also characterize JCF by performing inverse dynamics, but with addition of the third order polynomial muscle recruitment criterion applied in musculoskeletal model using AnyBody Modelling system.

Both articles in agreement on the findings state that, ankle joint contact force was decreased either during downhill running or walking which indicate decreased positive ankle work. Instead of that, hip, tibiofemoral and patello-femoral joint contact forces are increased with the increased of declination while uphill walking increased all lower joint forces.

| No | Author | Objective | Independent variable | Dependent variable | Method used | Findings |
|----|--------|-----------|----------------------|--------------------|-------------|----------|
| 1  | Park et al.[3] | To compare the effect of incline surface on kinematic and kinetic parameters during moderate and steep downhill running with level running. | Surface inclination (Level 0°, Moderate -6°, Steep -9°) | Joint forces 3D joint angles Moments Powers Work | Motion capture system – collect kinematic and kinetic data Visual 3D software – calculate three-dimensional joint angles, moments, powers and work Inverse dynamic – calculate joint force and moment | Runner alter their running mechanics and led to greater kinetic demand on knee to absorb load and energy during downhill running. |
| 2  | Alexander & Schwameder[4] | To investigate the lower limb joint compression forces and tibiofemoral joint shear force during incline walking at different slope. | Surface inclination (0°, ±6°, ±12° & 18°) | Joint compressio (for lower limb (hip, tibiofemoral, patellofemoral & ankle) | Vicon Nexus – process kinematic data AnyBody Modelling System (musculoskeletal model) – calculate lower limb joint force | Downhill walking resulting to increased hip, tibiofemoral & patellofemoral joint forces and decreased ankle joint compression forces, while uphill walking increased all lower limb joint forces. |
4. Discussion
Muscle reaction and joint force are related to each other and susceptible to injury [20]. Overcorrecting on certain injury might detrimental on bone, cartilage, musculoskeletal limb and posture. In order to further understand injury risk, this review is completed to compile and outline the published researches that related to biomechanical effects of incline gait in terms of muscle and joint force from the year 2009 until 2019.

Based on the review, there is variability of methodological application selected. However, all findings of the previous studies in this review are consistent which suggested that muscle response and force significantly changes according to the changes of surface inclination except for findings reported by Slaughter et al. [13]. It may be the case therefore that these variations of methodological application showed the flexibility of muscle and joint force measurement.

There are some limitations related to this review. This review only including English-based published articles. Thus, some articles may have been neglected. Other than that, the involvement criteria of the selected articles limited to muscle and force findings only. Thus, other biomechanics effects related findings articles were excluded.

5. Conclusion
As conclusion, there are different methodological applications have been introduced in investigating muscle response and joint force respectively so far. One of the issues that emerges from this review is limited studies assess both muscle response and joint force in an experiment, even though both are the main contributor to injury. Future studies which take these variables into account are therefore recommended with in addition of ligamentous force determination. This is because force validation that including muscle force which implement generic musculoskeletal model (not including ligament element) are not fully validated [21]. The study should be done in order to ensure a valid joint force determination in investigating injury risk due to surface inclination.

Acknowledgement
The authors would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2016/TK03/UNIMAP/02/6 from the Ministry of Education Malaysia.

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