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RESEARCH ARTICLE

Effect of Different Terrain Inclinations on Kinetic and Kinematic Parameters of Ankle Joint During Walking

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Abstract

The purpose of this study was to investigate the effect of walking up three ramps of different slopes (5º- 10º- 15º) on the two peaks of the ground reaction force (GRF), the ankle plantar flexion (PF) and dorsiflexion moments (DF) and the angular displacement of the right ankle joint in two different positions. The first position was the right foot inclination, left foot inclination in which both legs were placed on a ramp of the same slope. The second position was the right foot horizontal, left foot inclination in which the right leg was in direct contact with the horizontal ground and the left one was on a ramp. Thirty male students participated in this study. Their mean age, weight and height were 19.95 (±2.56) years, 73.73 (±6.44) Kg and 175.33 (±3.50) cm respectively. Each student was asked to walk up the three ramps in both positions. Data collection was carried out using the 3-D Motion Analysis System in conjunction with a force platform. The subjects were instructed to perform three trials during walking up each slope in the first and the second positions. Results revealed that in the first position there was no significant difference among the three tested ramps for each of the two peaks of the GRF. There was also no significant difference in the mean value of the ankle PF moment among the three tested ramps while there was a significant increase in the mean value of the ankle DF moments occurred at ramp 10º in relation to ramp 5º & ramp 15º reaching its minimum value at a ramp of 5º. In addition, in the second position there was a significant increase in the mean value of the 2nd peak of the GRF occurred at ramp 15º in relation to ramp 5º. While there was no significant difference among the three tested ramps for each of the ankle PF/DF moments. Consequently, it was concluded that walking up a ramp of 5º is much more preferable than walking up ramp of either 10º or 15º. This to decrease the demand on the dorsiflexors.

INTRODUCTION

As walking up and down slopes became more integrated in many rehabilitation programs, the demand on determining the best angles of inclination of these slopes has increased tremendously. The angles of inclination of the supporting surfaces are reported to play an important role in reducing the effort exerted around the ankle joint while walking, the slips and fall-related injuries. Not only do the angles of inclination affect the effort and the slips, however, it was found that they have important implications in prosthetics, and assistive devices.

The electrical activity of the gastrocenemius (GC), rectus femoris (RF), gluteus maximus (GM) and tibialis anterior (TA) muscles during walking up and down ramps of 0º, 15º and 39º was studied by Andrea et al. (2005).

They found that during stance phase of up slope walking the mean activity of the RF increased significantly as the walking grade increased and the activity of the GM at 15º and of the TA at 15º and 39º also increased. While during down slope walking the GC showed a significant reduction in mean activity and the RF and TA showed increases in mean activity levels as the walking grade changed from 0º to 39º.

The biomechanical approach for slips and fall studies has investigated human reaction to slips and falls. There appear to be two different directional slips during normal walking steps: forward and backward slip during the landing phase and backward slip during the take off phase (Redfern et al. 2001). The effect of load carrying and floor contaminants on slips and fall parameters was studied by James (1997). Four different floor surfaces: oily vinyl tile, dry stainless steel, oily plywood and dry ceramic tile were prepared for ten subjects with each walking at a fixed velocity while carrying five different loads: no external load, load of 20% of the body weight, load of 40% of the body weight, 18 Kg and 24 Kg loads carried in a container held against the body. A programmer slip resistance tester was used to measure dynamic coefficient of friction with conventional set up value for heel velocity. On oily floor heel velocity of 60 to 40 cm/s would be recommended because faster transfer of the body weight was seen owing to decreased stride length. The results showed that there was an abnormal gait pattern, short stride length during walking on oily floors or with heavy load carriage because subjects adjusted their stride length for a better stance.

One of the factors that may affect the generated moment around the ankle joint during walking up a ramp is the mechanics of ankle\ foot complex (Neumann 2002). Some neurological problems of foot like drop foot and spastic foot were demonstrated by Perry (1992). In drop foot, there is low heel and forefoot contact occurs when the foot strikes the floor with the ankle in 15º plantarflexion and the knee fully extended and entry into loading response phase would be sudden. While in spastic foot, there is persistent ankle plantar flexion during walking and inability to rise on the metatarsal heads.

Thus, management of foot dysfunction requires the designers of medical shoes to use specifically wedged insole. The kinematic and kinetic effect of wearing laterally wedged insole on knee joint moment during gait in normal healthy adult was assessed by Kakihana et al. (2004). The study was conducted with 3-D motion analysis and ground reaction force analysis using force platform, when subject walked under 3-different insole condition:- no-wedge, low wedge and a high wedge. The results obtained indicated that under dynamic condition, the subject wearing laterally wedged insole increased the moment at the subtalar joint and decreased it at the knee joint via the more laterally shifted center of pressure.

The effect of different elevation of laterally wedged insoles with subtalar strapping on medial compartment osteoarthritis of the knee was reported by Toda et al. (2004). Sixty-two women with knee osteoarthritis were randomized into 3 groups according to wedge elevation. Participants wore laterally wedged insole with subtalar strapping with elevation of 8, 12 and 16 mm for 2 weeks. Radiographs were used to analyze the femorotibial angle for each subject, both with and without insole. Results indicated that the 16 mm group showed a significantly greater valgus correction of femorotibial angle than the 8 mm group. The score was significantly improved in the 12 mm group compared with the 16 mm group. The degree of change in femorotibial angle using the insole with subtalar strapping was affected by the tilt of the lateral wedge. The 8 or 12-mm elevation wedged insole with subtalar strapping may be more comfortable and effective than the 16-mm elevation wedge. From this information it is obvious that using different wedge insoles not only affected the range of motion and moment of ankle /foot complex but also affected the knee joint's moment.

As it is obvious, the angles of inclination of the supporting surface have a great impact on the effort exerted around the ankle joint, the fall-related injuries, the prosthetics, and assistive devices. This might be attributed to change in the normal mechanics of the ankle\ foot complex.

Finley and Cody (1970) and Sun and Walter (1996) studied the characteristics of pedestrians on inclines by simply observing pedestrians in a pre-characterized setting (i.e. a pre-defined walkway distance on a measured incline). Finley and Cody (1970) recorded the number of steps and time required for 1106 urban pedestrians to traverse a marked distance. The locations used in their study had inclines up to 4° and equal numbers of pedestrians were observed walking uphill as walking downhill. While Sun and Walter (1996) performed a more comprehensive investigation of pedestrian gait parameters during walking on sloped surfaces; they observed 2400 pedestrians walking up and down a ramp whose incline ranged from 2° to 9° and recorded subject gender, the number of steps taken and time required to traverse a marked distance. They found that for uphill walking the mean walking speed, cadence and step length decreased significantly with increasing slope while during walking downhill, walking speed and cadence did not significantly vary with slope.

However, there is a lack of information regarding the effect of sloped surfaces on the magnitude of ground reaction force and the moments around the ankle joint while walking so the purpose of this study is study the effect of walking up ramp of three different inclinations (5º-10º- 15º) on the generated moment around the ankle joint of normal subject and to select the angle of inclination to be used for walking easily.

Statement of the problem

- Would different walking ramps affect the moments around the ankle joint during normal walking?
- Would different walking ramps affect the magnitude of the vertical ground reaction force?
- Would different walking ramps affect the angular displacement of the ankle joint?

Purposes of the study

The purposes of this study are

- To explore the effect of walking on different ramps on the ankle joint moments.
- To investigate the effect of walking on different ramps on the magnitude of vertical ground reaction force.
- To plot the angular displacement of ankle joint while walking on three different ramps.

Significance of the study

It is hoped that this study will help ergonomists to ergonomically design the slope which helps handicapped subjects to walk easily and safely in rehabilitation centers, industrial factories and in hospital. The attempt of changing ankle position by providing different angle of inclinations might contribute to the reduction in the effort experienced by subjects during walking.

Based on the outcome of this study it might be possible that designers of medical shoes will select the appropriate wedged insole for drop foot patients and spastic patients. This is to protect the foot from being dragged.

The results might additionally help in the prognosis and management of coronary artery disease. It could be used to add information to that produced by the ECG studies. This might enable the cardiologists to asses the effect of walking on inclined surfaces on the patient‘s health.

Delimitation

The study is delimited to

- Mechanical analysis throughout the stance phase of the gait cycle.

Limitation

The study is limited by

- The psycho-physiological condition of the students at time of performance.
- Variation of functional activity level among the students
- The variation of time of examination.

Assumption

It is assumed that

- All subjects are under normal psycho-physiological condition.
- All subjects will conduct and follow instruction carefully.

Hypotheses

The null hypotheses of this study are:

- There is no difference in the magnitude of the moments around the ankle joint with different walking ramps.
- There is no difference in the magnitude of the vertical ground reaction forces with different walking ramps.
- There is no difference in the angular displacement of the ankle joint with different walking ramps.

Literature Review

Bipedal locomotion or gait is a functional task requiring complex interactions and coordination among most of the major joints of the body; particularly of the lower extremities (Frankel and Nordin 2001). It is also the most convenient means of walking short distances. Functional versatility allows the lower limbs to readily accommodate stairs, doorways, changing surfaces, and obstacles in the path of progression. Therefore, walking on a level surface requires a repetitious sequence of limb motion to move the body forward and simultaneously maintaining stance stability (Perry 1992).

Walking on uneven surface or different terrains result in different gait parameters and changes the characteristics of gait. Thus, compensatory patterns of motion around body ‘s joints are observed. Walking down an inclined surface has been found to have an effect on some kinematics variables when compared to walking on a level one (Sun and Walter 1996 and Red fern and Dipasquale 1997). Sun and Walter (1996) determined the walking speed, cadence and step length for 2400 subjects while walking down a ramp of 2º to 9º. The most significant finding was that the step length was greatly decreased by an increase in the ramp angle. They also reported that a reduction in the step length produced a reduction in the friction demand that would be required at heel strike during downhill walking and increased the incidence of slips and falls.

As walking down a ramp is important to prevent fall related injuries and provide safer environment for workers, walking up a slope has a great role to help handicapped subjects and workers walk easily and safely whether in rehabilitation centers, industrial factories or elderly patients at hospitals. Thus, studying the biomechanics of walking up a slope is important to change ankle position by providing different angles of inclinations that may significantly contribute to the reduction in the effort exerted by subjects during walking over them.

- **The normal gait mechanics:**

Walking is the body‘s natural means of moving from one location to another. It involves a series of interactions between two multi segmented lower limbs and the total body mass.

Identification of the numerous effects that occur necessitates viewing gait from several different aspects. There are three basic approaches: the simplest approach subdivides the cycle according to the variations in reciprocal floor contact by the two feet; the second approach uses the time and distance qualities of the stride; and the third approach identifies the functional significance of the intervals within the gait cycle and views these intervals as the functional phases of gait (Perry 1992).

A full gait cycle (GC) is defined by the occurrence of a sequential stance phase and swing phase by one limb, or a stride (Frankel and Nordin 2001). A gait cycle is also reported by Ranawat and Positano (1999) to consist of two steps and is defined as the time which ranges from a specific event on one limb to the same event on the ipsilateral limb. The distance covered during one gait cycle is termed stride length.

Each gait cycle was divided into two periods: stance period (60% of GC) and swing period (40% of GC). These often are called gait phases. Stance is subdivided into three intervals according to the sequence of floor contact by the two feet (double stance); while the middle portion of stance has one foot contact (fig. 1). Stance begins at initial contact and ends as soon as the foot leaves the ground. It divided into two phases which are weight acceptance and single limb support. The weight acceptance consisted of two sub phases which are initial contact and loading response while the weight acceptance consisted of three sub phases which are mid stance, terminal stance and pre swing phase. In normal gait, the last segment of the foot to clear the ground is the hallux, and thus the final stance event is often referred to as toe off. Swing begins at toe off and ends in the following initial contact. It divided into the limb advancement phase which consisted of three sub phases which are initial swing, mid swing and terminal swing. (fig. 2) (Perry 1992).

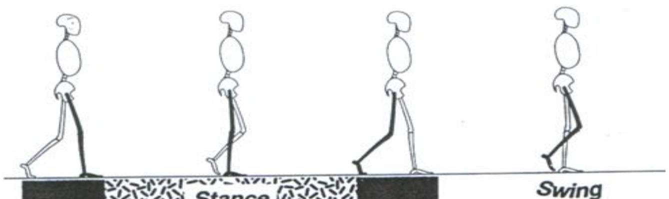


Fig. 1: The subdivision of stance and their relationship with the bilateral floor contact pattern. (Adapted from Perry 1992).

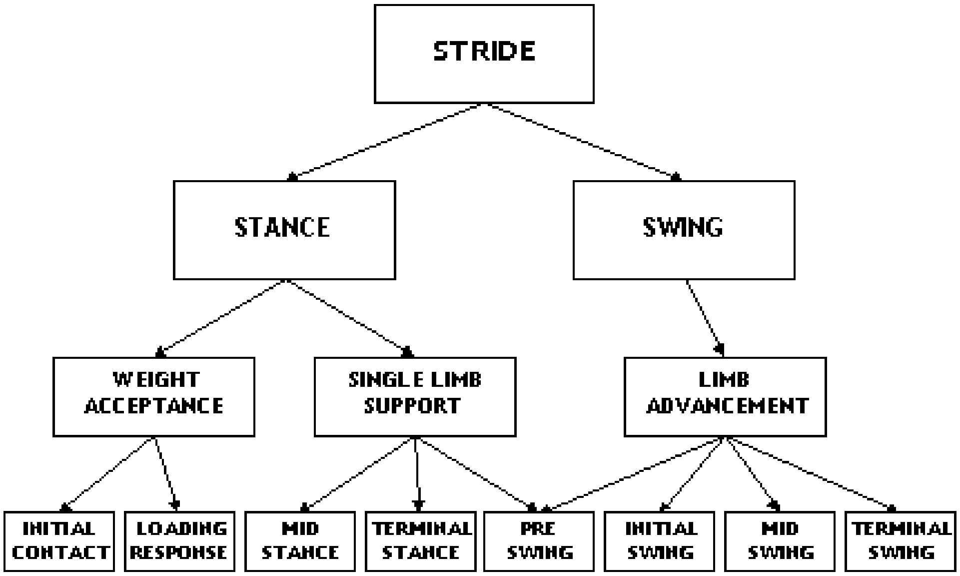


Fig. 2: Divisions of the gait cycle. (Adapted from Perry 1992).

Analysis of a person's walking pattern, more directly, through phases identifies the functional significance of the different motions occurring at the individual joints. The phases of the gait also provide a mean for correlating the simultaneous actions of the individual joints into a pattern of total limb function. This is a particularly important approach for interpreting the functional effect of disabilities (Perry 1992).

Walking velocity influences the exact distribution of the gait cycle between stance and swing. At free velocity of 80 m/min, stance and swing are 62% and 38% of the gait cycle. At faster velocities, the relative percentage of swing increases and stance decreases (Lavoie et al. 1995, Lelas et al. 2003). In addition, excess walking velocity is associated with the increase in both cadence and stride length and the decrease in the absolute time spent in swing and support (Ranawat and Positano 1999).

- **Mechanics of the ground reaction force:**

1- Components of the ground reaction force:

In gait, the main external forces acting on the body are gravity, inertia and ground reaction force (GRF) (Cynthia et al. 1992). The ground reaction force describes the reaction force that is provided by the supporting surface on which the movement is performed (fig. 3). It is derived from Newton's law of action-reaction to represent the reaction of the ground to the accelerations of all body segments (Enoka 2002).

Figure (3) shows that during walking, the reaction force which is applied at the heel during the initial contact phase (a) or at the toes during the preswing phase (c), can be resoluted into vertical component (Fv) and horizontal component (Fx). The magnitude of these components depends on the angle of the force application, which is related to the step length. The angle of the force application is the angle between the reaction force line (F) and the vertical line

(V). If the step length is short and the angle of the force application is small, the horizontal force component decreases (Fsinθ) similarly. When the step length is longer and the angle of the force application is greater, the horizontal force component increases. Excessive increase in the horizontal force component causes slipping of the subject unless this component is opposed by frictional force. This means that, the frictional force at the foot must be greater when the step is longer than when it is shorter. While in figure (3b), the effect of the reaction force applied to the foot during the midstance phase is entirely rotatory as there is no horizontal component, thus, it can not be resoluted (Simonsen et al. 2002).

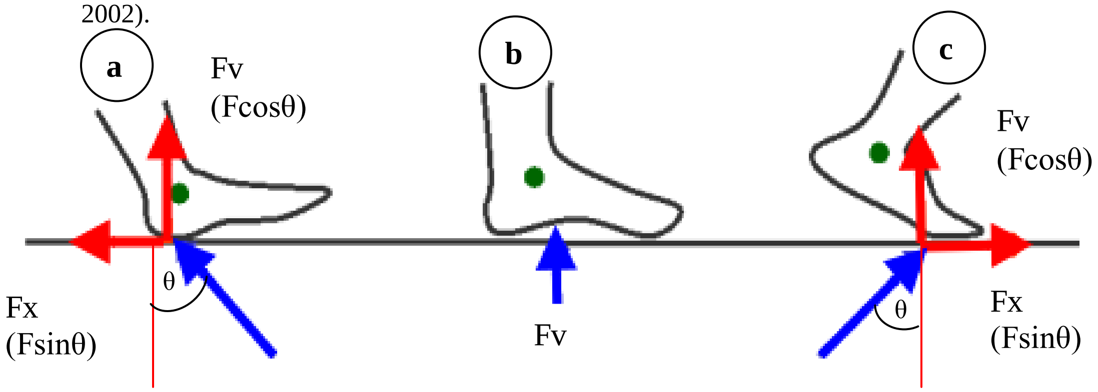


Fig. 3: The forces applied to the body by the ground when an individual takes a step. (Adapted from Simonsen et al. 2002).

The description of the ground reaction forces follows a certain coordinate system, with the forces being expressed along three orthogonal axes: Fz vertical (up-down); Fy, antroposterior (forward-backward); and Fx, mediolateral(side-to-side) (fig. 4). The vector summation of the three forces gives a single resultant force vector between the foot and the ground, which leads to the classic butterfly representation of the ground reaction forces for a single step (Neumann et al.2002, Hamill and Knutzen 2003).

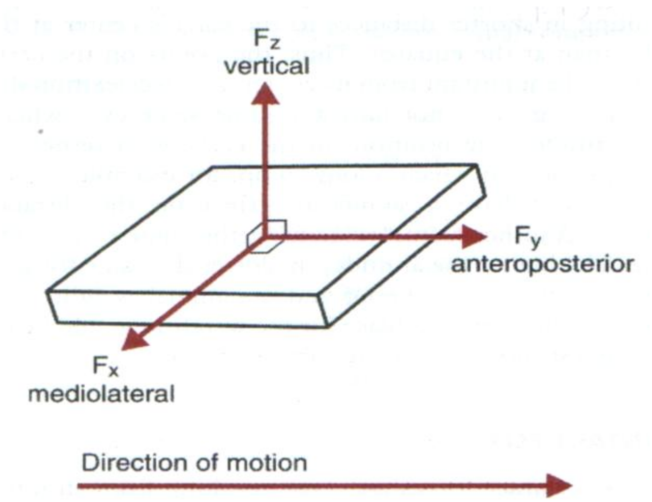


Fig. 4: Ground reaction force components. (Adapted from Hamill and Knutzen 2003).

The magnitude and direction of the ground reaction force changes throughout the stance phase of each foot and is directly related to the acceleration of the body's centre of mass (COM). The centre of mass of the body rises and falls as the individual moves from double support to single support. Similarly, COM moves from side to side as the individual passes from stance on the right to stance on the left (Kram et al. 1997 and Enoka 2002).

The vertical component of the GRF is characterized by a double-humped curve which has two peaks and valley. The two peaks (F1 and F3) represent more than 110% of the body weight while the valley between the two peaks (F2) represents less than 80% of body weight (Simkin 2001).

In the event of loading response, the first peak (F1) occurs, as the body's COM moves downward thus is needed to initially decelerate the downward movement of the body and then accelerate it upward. While in preswing, the second peak of the GRF (F3) occurs, reflecting the combined push provided by the plantar flexors and the need to reverse the downward movement of the body′s COM. During midstance, the valley (F2) is created by the rise of COM as the body rolls forward over the stationary foot (Neumann 2002).

The equation that controls the vertical load is: F = M (g + a) where (F) is the vertical force, (M) is the person′s mass, (g) is the gravitational constant and (a) is the vertical acceleration. The vertical force changes with changing the vertical acceleration (a). If a = 0 the force is the body weight (BW) and if a > 0 the force goes up and if a < 0 the force drops below body weight (Perry 1992).

The posterior and anterior shear component of the GRF also demonstrates a consistent pattern in normal locomotion. The ground exerts a posterior force on the foot during the initial portion of stance decelerating the foot. During midstance, the ground places an anterior shear force on the foot, contributing to the forward propulsion of the body. The medial and lateral shear forces during gait are smaller and more variable than the vertical forces or posterior-anterior shear forces. They reflect forces associated with the shift of the body from side to side between the supporting feet (fig. 5) (Simkin 2001 and Oatis 2004).

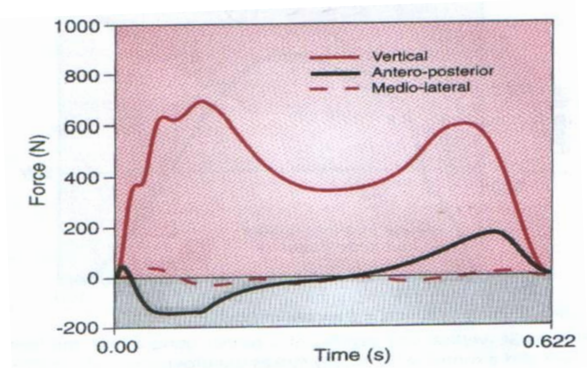


Fig. 5: Normal GRF pattern during stance. (Adapted from Oatis 2004).

The GRF can be measured with an instrument known as a force platform, embedded in the walking surface which essentially operates like a scale for measuring a weight (Enoka 2002). There are four 3-axial force sensors embedded in the plate, one in each plate corner, so that one can measure the ground reaction force in 3 axes: antero-posterior axis (X axis), transverse axis (Y axis) and vertical axis (Z axis) shown in figure (6 a). Figure (6 b) shows the reactions from the ground to the foot. The sum of all the reactions from the ground shown in figure (6 b) is equivalent to the sum of the forces measured by the four force sensors in the plate (F1+ F2+ F3+ F4) shown in figure (6 c). The ground reaction force (F) is the sum of these forces as shown in figure (6 d) (Mueller et al. 1995).

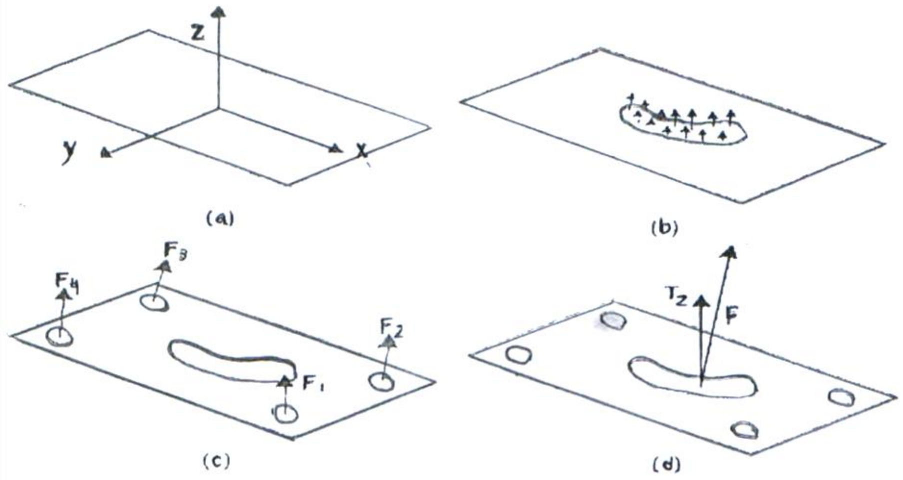


Fig. 6: (a) the reference frame of the force plate and the measured 3 axes of the GRF vector. (b) The reaction force vector from the ground to the foot. (c) The four force sensors in the force plate and (d) the sum of the 3 component of the GRF. (Adapted from Mueller et al. 1995).

Therefore, the GRF has three components: Fx, Fy & Fz (Rx, Ry& Rz). Among these, the x-component is along the direction of the motion which reflects the propulsion force. The z-component is used to support the body so that to prevent the body from collapsing.

During locomotion, forces applied to the foot from the ground correspond to the centre of pressure which represents the point of application of GRF at the foot. The path of the centre of pressure (COP) under the foot throughout the stance follows a relatively reproducible pattern. At heel contact, the COP is just located lateral to the midpoint of the heel. Then, it moves to the lateral midfoot region at midstance and to the medial forefoot region during heel off to toe off (Hamill and Knutzen 2003). Investigation of this plantar loading pattern of the foot reveals that the largest vertical loads and pressure are generated under the heel at ground contact (Cavanaph et al. 1987). Peaks pressure of 13 to 14 Mpa is reported during standing (Oatis 2004). While during walking, it was reported by Grampp et al. (2001) that the mean value of the peak pressure was distributed on the foot regions as follow: 136.8 Kpa on the heel region, 159 Kpa on the 1st metatarsal, 174.8 Kpa on the 2nd and 3rd metatarsals, 137.8 Kpa on the 4th and 5th metatarsals, and 103.5 Kpa on the lesser toe (fi

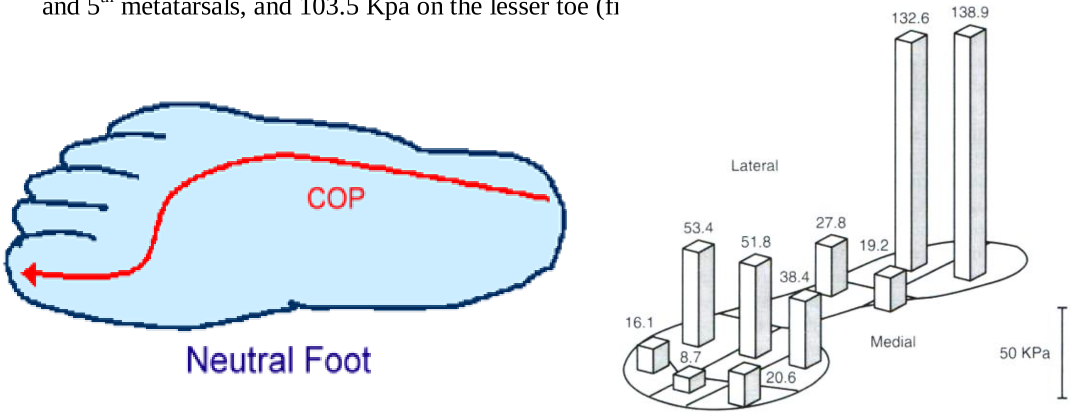


Fig. 7: The pathway of the COP and plantar loading pattern distribution of the foot. (Adapted from Oatis 2004).

2-The relation between the GRF and the internal joint moment:

During gait, the GRF applied under the foot generates an external moment on the joints of the lower extremities. Moment is defined as the product of the force and its lever arm (M = F× LA) (fig. 8). The lever arm is the perpendicular distance between the line of the action of the muscle and the centre of the joint (Perry 1992).

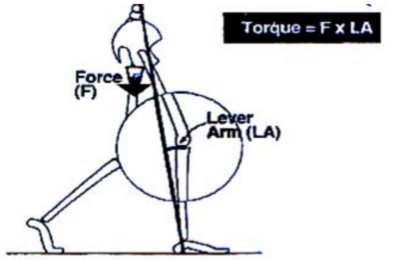


Fig. 8: The effect of external moment on the joints of the body. (Adapted from Perry 1992).

In quiet standing, the alignment of the body’s COM relative to the joint axes defines the external moments applied to the joints. Tests of the external moments applied to the joints of the lower extremities, trunk, and head by GRF help explain the forces needed to support these joints (fig. 9) (Oatis 2004).

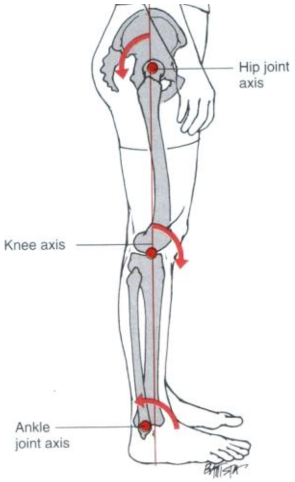


Fig. 9: Alignment of GRF during quiet standing. (Adapted from Oatis 2004).

From heel strike to foot flat, the line of action of the GRF is located behind the ankle and the knee, but anterior to the hip. Consequently, the GRF produces ankle plantar flexion, knee flexion, and hip flexion to avoid the collapse of the lower extremities. These external moments are resisted by internal moment created by ankle dorsiflexion, the knee extensors, and the hip extensors (fig. 10) (Simonsen et al. 2002 and Neumann 2002).

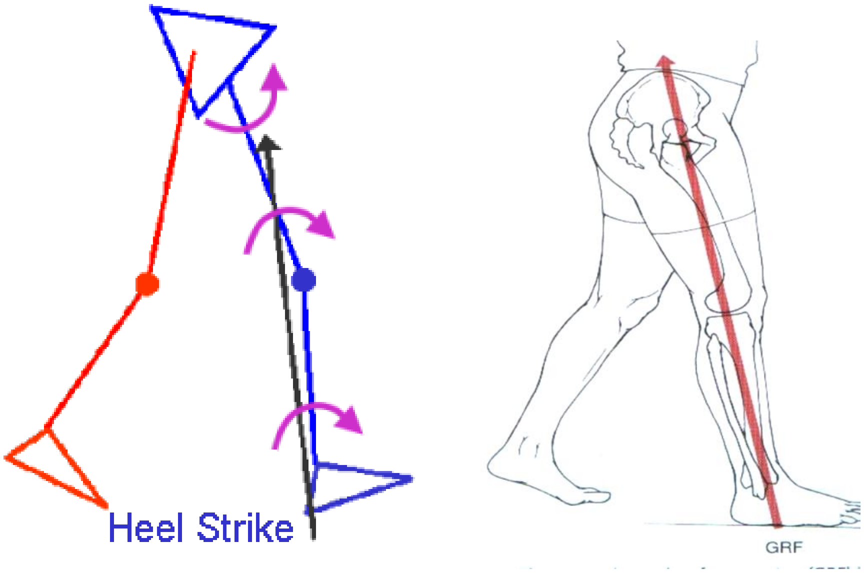


Fig. 10: The pathway of GRF vector from heel strike and foot flat. (Adapted from Simonsen et al. 2002).

Internal joint moment refers to those created by the muscles, soft tissue and joint contact forces which are necessary to keep the body upright against the gravitational forces and moving it forward (Frankel and Nordin 2001). It has been found in the sagittal plane analysis of the internal moment that there is a small dorsiflexion moment of 0.2 Nm/kg generated at the ankle joint immediately after heel contact, as the foot is lowered to the ground. This moment serves to eccentrically control the movement of the plantar flexion generated by the application of the body weight on the calcaneus (Neumann 2002).

During the late stage of the stance, when the body passes over the stance foot, the ground reaction force tends to extend or dorsiflex, the metatarso phalangeal joint of the great toe. This extension moment is balanced by a flexion moment produced by the planterflexors muscle force (fig. 11) (Oatis 2004). Consequently a transition to a net ankle plantar flexion moment occurs throughout the rest of the stance, to control the tibial advancement over the foot, then to plantar flex the ankle at push off.

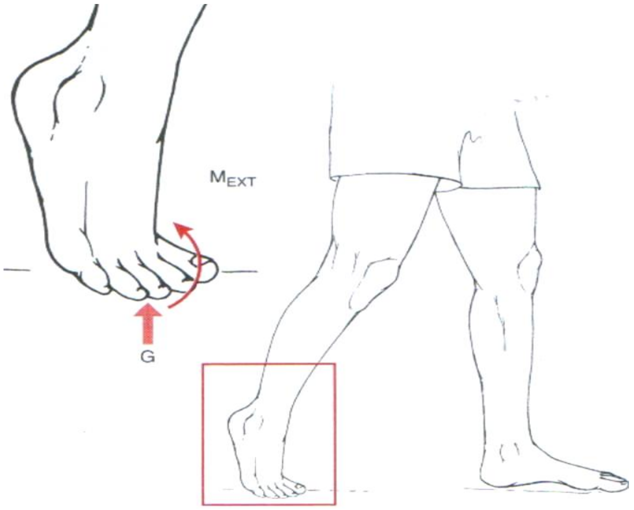


Fig. 11: The GRF applies an extension moment on the toes as the body rolls off the stance foot. (Adapted from Oatis 2004).

The plantar flexion moment peak is 1.6 Nm/kg at 45% of the stride, while a very small dorsiflexion moment following toe off pulls the foot and toes away from the ground to keep the ankle dorsiflexed during swing phase (Frankel and Nordin 2001, Hamill and Knutzen 2003 and Oatis 2004). The main compressive force of five times body weight (B.W) across the normal ankle while walking was produced in late stance by contraction of the gastrocenemius and soleus muscles. In vivo determination of Achilles tendon forces reveal average peak forces of 1430 N during gait (Finni et al. 1998), while the pretibial musculature produces mild compressive forces in the early stance of gait that are less than 20% B.W (fig. 12) (Simonsen et al. 2002).

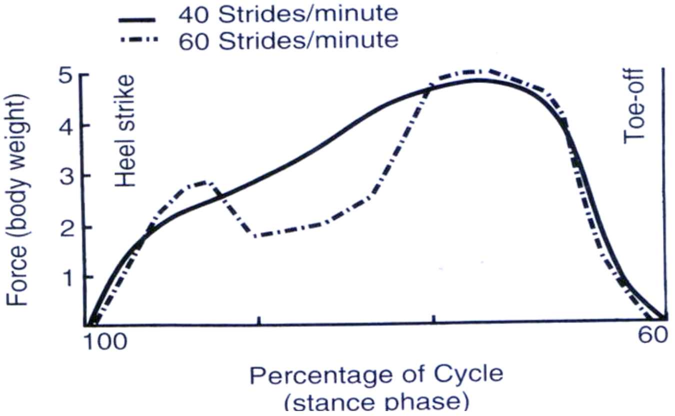


Fig 12: The compressive force produced by contraction of calf muscles during the stance phase of gait at two velocities. (Adapted from Frankel and Nordin 2001).

In the frontal plane analysis, there is a small initial eversion moment at the subtalar joint (from 0% to 20 % of gait) due to medially alignment of the ground reaction force vector over it (fig. 13). This eversion moment is followed by an inversion moment (from 2% to 45 % of gait), therefore the subtalar joint with the anterior articulation between the talus, calcaneus and navicular are subjected to forces as high as 2.8 B.W while walking (Czerinie and Rodgers 1988).

In the horizontal plane, an external rotation moment referred to as an abduction moment is presented during the stance phase (Neumann 2002). These internal moments in the frontal and horizontal planes are smaller than those in the sagittal plane (Oatis 2004). It was described by Hof (2000) that the support moment for the stance phase of gait is considered to be the sum of internal sagittal plane moments into which all of the moments tend to push the body away from the ground or to support the body (fig. 14) (Oatis 2004).

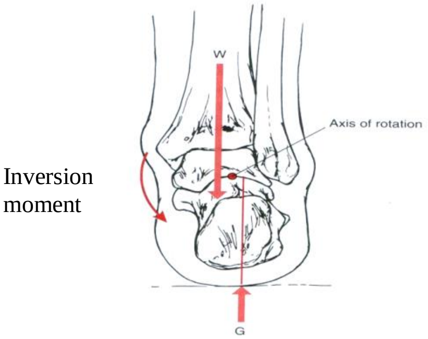


Fig. 13: Moment generated by GRF at subtalar joint in the frontal plane during 1st part of the stance. (Adapted from Oatis 2004).

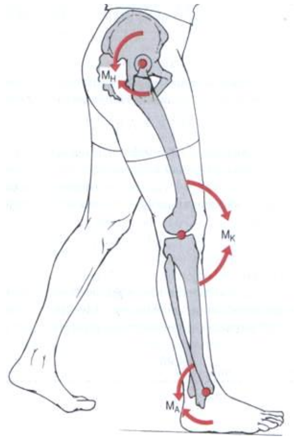


Fig. 14: Support moment is the sum of internal moment at the hip, knee and ankle joints. MH: moment at the hip joint, MK: moment at the knee joint and MA: moment at the ankle joint (Adapted from Oatis 2004).

The product of internal moment at a given point in time and a joint angular velocity can be defined as joint power which indicates the generation or absorption of mechanical energy produced by muscle groups. Therefore, it fluctuates continuously throughout the gait cycle (Frankel and Nordin 2001). Power is a useful indication of the muscle's role in controlling motion; it is negative when the body absorbs energy and positive when it generates energy. Thus concentric muscle activity generates power, and eccentric activity absorbs power (Winter et al. 1983).

Analysis of joint powers makes us understand of the role of the muscles in propelling and controlling movement during locomotion (Sadeghi et al. 2000 and Rilley et al. 2001). The joint powers at the ankle demonstrate a high magnitude power generation of 2-3 watt/kg at the end of the stance when the plantar flexors contract concentrically. Thus they are responsible for a large portion of the propulsive forces pushing the body forward while walking (Neumann 2002 and Oatis 2004). The moment of force and powers while running are greater in magnitude than those while walking, as the lower extremity moments of force increase in magnitude with an increase in locomotor’s speed (Ounpuu 1994).

3- The relation between the joint forces and the reactive force:

Ankle joint surface, ligament and tendons are all subjected to large tensile, compressive, or shear forces while walking. These forces which act on the ankle joint during gait are equal to or greater than the hip and knee joints respectively and are referred to as joint reaction forces. Therefore, knowledge of the magnitude of this force is of importance, especially for the clinician, orthopedic surgeon, and bioengineer (Neumann 2002, Hamill and Knutzen 2003).

Mathematically, the relation between the joint forces and the reactive forces was calculated as shown in (fig. 15). The leg is imagined to be divided into three segments foot, lower leg and upper leg linked by hinge joints. The reaction force R2 with its components R2x and R2y and the moment M2 act on the distal end of the lower leg, while the reaction force R3 with its components R3x and R3y and the moment M3 act on the proximal end of the lower leg. It was found that the reaction forces transmitted from the neighboring segmented are not identical to the joints forces, but rather represent the net force transmitted from one segments to the next (Biewener 2002).

It was also reported by Van den et al. (2000) that the external forces that occur during locomotion can be integrated with the kinematic data in a process called ‘Inverse Dynamics’ to calculate the internal forces at each joint (fig. 16). The inverse dynamics process assumes that at a finite time point the limb is not moving and can be divided into rigid segments (foot, shank and thigh). Starting with the isolated foot segment, the known variables are the external forces (measured), the segment mass (calculated), and the COG linear and angular velocity and acceleration (calculated). Using Newton’s laws the two unknown variables, the force and moment at the ankle joint center, can therefore be calculated.

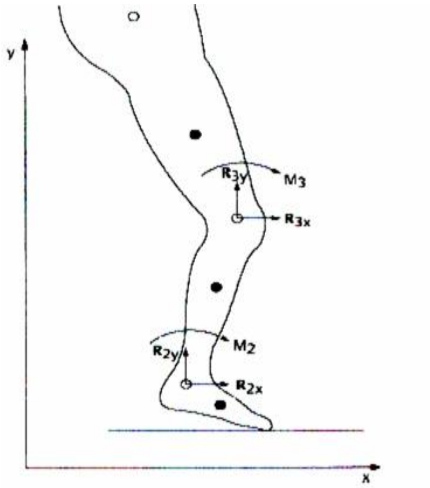


Fig. 15: Reaction forces R2 and R3 and reaction moments M2 and M3. (Adapted from Biewener 2002).

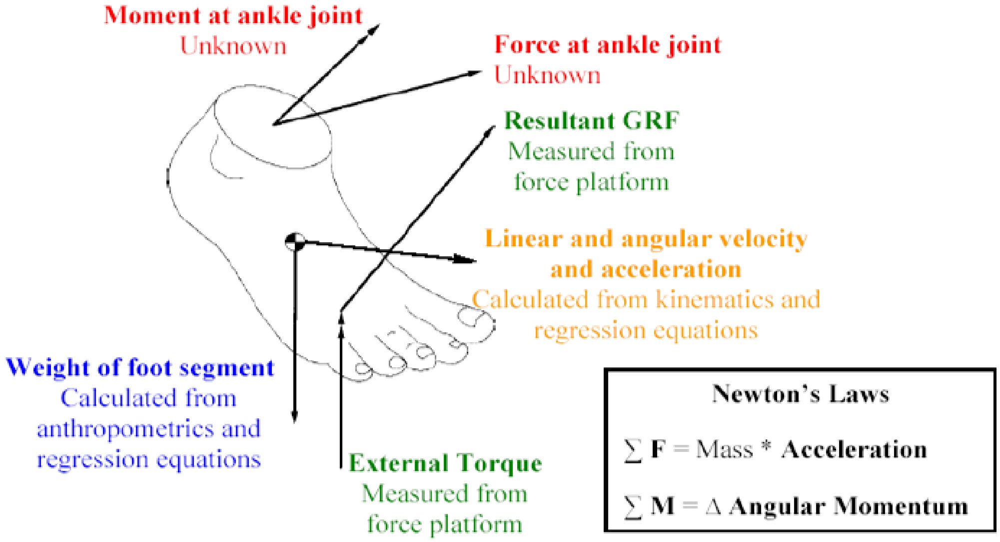


Fig. 16: The Inverse Dynamics Process. Forces and Newton’s laws are used to calculate the unknown force and moment at the ankle joint. (Adapted from Van den et al. 2000).

The pattern of ankle joint reactive force during gait differs with different walking cadence. In a faster cadence, the pattern showed two peak forces of three to five times B.W one in the early stance phase and the other in late stance one. In the slower one, early one peak force of five times B.W was achieved during late stance phase (Frankel and Nordin 2001). While running, localized ankle forces may be as high as 10 to 13 times B.W (Scott and Winter 1990).

It was observed by Gowitzke and Milner (1992) and Michelson et al. (2001) that the talocrural articulation is quite congruent, which helps reduce joint stresses and reactive forces. In addition, the contact area between the talus and tibia and fibula of 11to 13 cm is so great that it can decrease stress especially with ankle plantar flexion.

Vertical ground reaction forces contribute significantly to joint reaction forces which in turn contribute to patient's pain with joint pathology, such as arthritis. As it was reported by Kaufiman et al. (2001) and Frankel and Nordin (2001) that on a free body diagrams of the leg and foot, the joint reaction force represented about 2.1 times of the body weight while the muscular force exerted by the plantar flexors, which are transmitted through the achilles tendon, represented about 1.2 times of the body weight during walking on a level surface at the pre swing phase (fig. 17). Therefore, patients with arthritis walk more slowly as the vertical ground reaction forces demonstrate smaller peaks and valley as a result of smaller vertical acceleration (Simkin 2001).

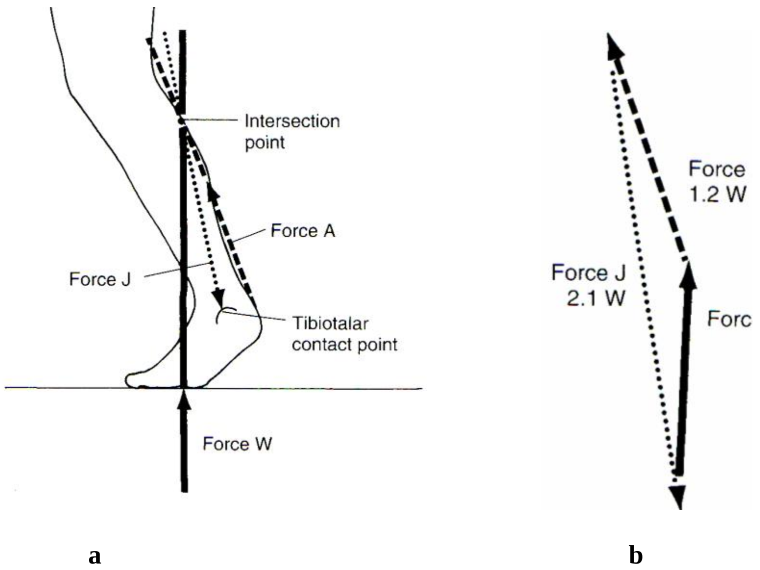


Fig. 17: (a) on a free body diagrams of the foot, including the talus, the lines of application for W and A is extended until they intersect. (b) a triangle of forces is constructed. (Adapted from Frankel and Nordin 2001).

- **Effect of uneven surface inclinations on human gait characteristics during walking:**

1- On the two peaks of the vertical GRF:

There are constant adjustments in ankle and foot joints in response to both the characteristics of the supporting terrain and the actions of the muscles that cross them, which provide a smooth interaction between the body and the wide variety of the supporting surfaces encountered while walking (Frankel and Nordin 2001). As, sloping walking surfaces provide a unique environment for examining the biomechanics and neural control of locomotion, it is a common challenge that places specific demands on the neuromuscular system (Andrea et al. 2005).

Measurement of the vertical GRF during walking on uneven surfaces like stairs was studied by many authors Winter (1991) studied the variation occurred in the magnitude of the vertical GRF during stair ascending. They found that the GRF demonstrated two peaks as walking on a level surface; however, the second peak tends to be greater than the first one. While during stair descending it was reported by Mcfayden and Winter (1988) that the GRF pattern varied significantly compared to that of the stair ascending. They observed that the first peak is much higher than that of the stair ascending while the second peak is much lower.

Riener et al. (2002) studied the value of the GRF during stair climbing at different inclinations (24º- 30º and 42º) and found that the mean values of the vertical GRF were not significantly affected by stair inclinations.

However, it was reported by Stacoff and Diezi (2005) that the average vertical GRF increased up to 1.6 B.W on the steep stair.

Measurement of the GRF during walking on different terrain as walking down a ramp was studied by (Charm and Redfern 2001). They stated that there was a decrease in the magnitude of the vertical GRF and shear forces during walking down a ramp of different inclinations of 5º- 10º- and 15º.

The force time pattern of older women walking on the level surface and descending both stairs and ramp was studied by Raynor et al. (2002). The results indicated that, the 1st peak of ground reaction force was greater than the 2nd one during walking down stairs and walking down ramp. In addition, the mediolateral and antroposterior shear forces achieved the greatest results during walking down ramp.

The kinetic of human locomotion on sloping surfaces was also studied by Andrea et al. (2005). They designed the walkway ramp system figure (18) consists of a two-segment walkway (A and B). Segment A provides a transition from the floor to segment B, which contains a force plate (C, 0.4m x 0.6m x 0.083m). This plate was vertically supported by Incline-specific Unistrut channel posts (shown schematically as G) Segment B is hinged to a platform (D, 0.52m long) at one end and to the shorter walkway segment (A) at the opposite end, where it is also mounted on 0.1m hard rubber swivel locking casters. The casters allow the ramp to move freely as the platform is raised or lowered. Two adjustable nylon base swivel leveling mounts are affixed to the walkway frame adjacent to the casters. Once the ramp is in the desired position, the mounts are lowered, lifting the casters off the ground, and supporting the lower end of segment B. The platform is mounted on a scissor lift (shown schematically as F) that is powered by a hydraulic pump. The platform and scissor lift are constrained by a 2.34m high tower (E) that also acts as a safety railing when subjects are standing on the platform.

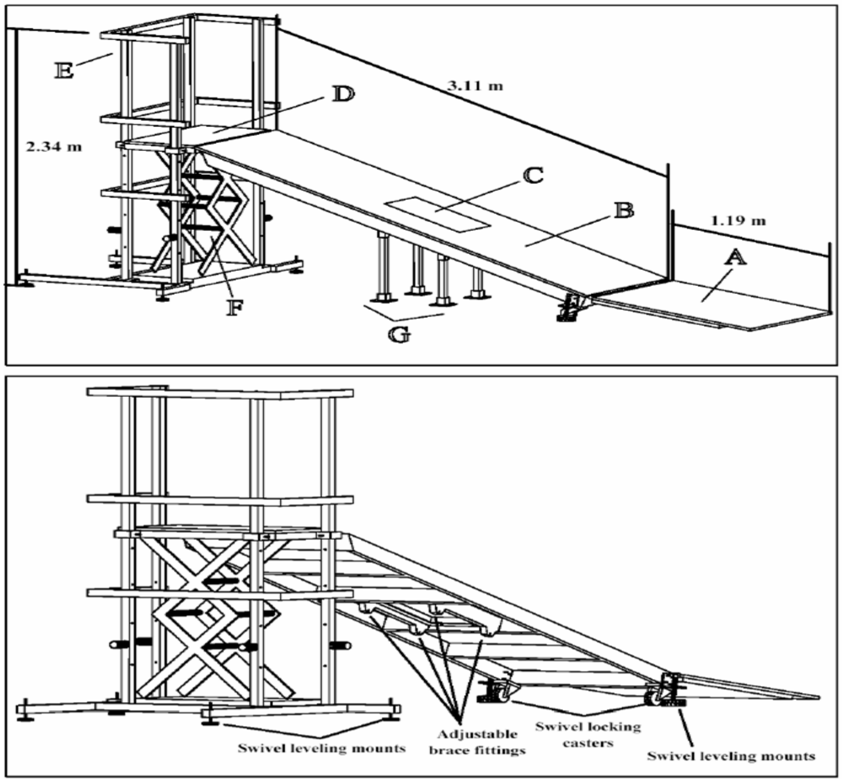
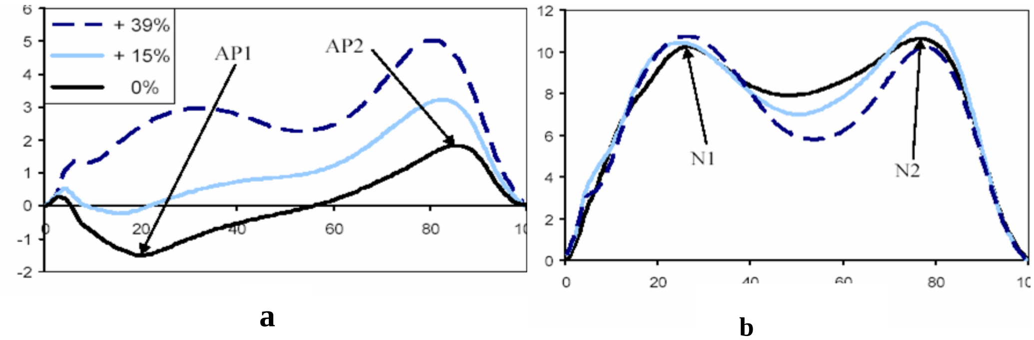


Fig. 18: The Ramped Walkway System. anterior-oblique view of the ramped walkway system showing the two segment walkway. (Adapted from Andrea et al. 2005).

They measured by the previous walkway design the GRF during upslope and down slope walking at 3 ramp grades (0º- 15º and 39º). They found that during walking up a ramp there was a significant effect for all GRF components except the peak vertical component during early stance (fig. 19). The early stance antero-posterior (AP1) force was negligible at 15º walking grade and increased at 39º grades, while the propulsive force (AP2) increased significantly with walking grade. The late stance vertical component peak and resultant force peak increased significantly at 15º but not at 39º walking grade. They also found that both the normal force and the resultant force decreased during midstance.

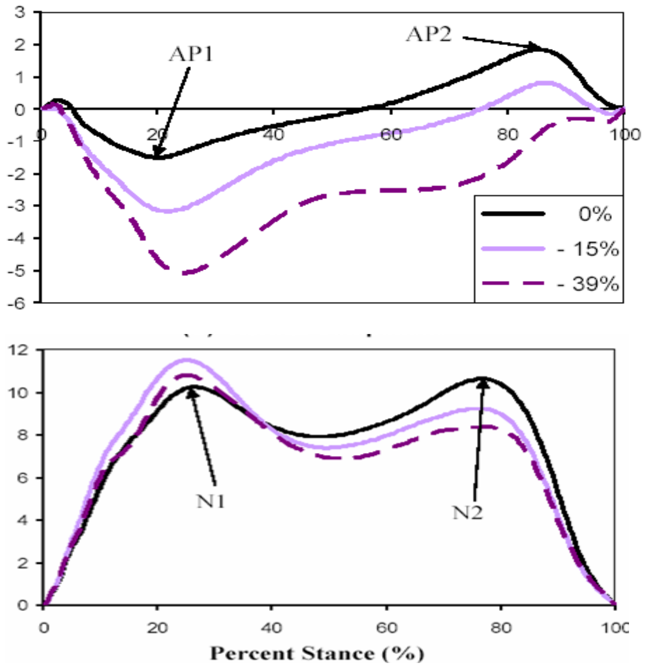
They also found that during walking down a ramp fig. (20) the first peak of the vertical component increased at 15º walking grade, but showed no change from level at 39º walking grade. They postulated that the steep slope of the ramp surface caused more of each subject's body weight to contribute to the shear (AP) component of the GRF, and therefore reduced the magnitude of the normal component.



a

b

Fig. 19: a- antero-posterior and b- vertical component of the GRF during walking up a ramp. (Adapted from Andrea et al. 2005).



a

b

Fig. 20: a- antero-posterior and b- vertical component of the GRF during walking down a ramp. (Adapted from Andrea et al. 2005).

The gait characteristics of 1200 female and 1200 male were recorded by Sun and Walter (1996) as they traversed a ramp of varying ramp. Walking speed, cadence and step length were determined for each subject and average population gait parameters for each ramp angle were also calculated. The most significant finding was that the step length decreased during ramp descends which produces a reduction in the friction demand. Also, a shortening of the stride length is probably a means of counteracting the higher friction demand that would otherwise be required at heel strike during downhill walking.

The plantar loading changes in case of 5 gradient conditions on a treadmill (-15%, -8.5%, level, 8.5%, 15%) for 20 participants were studied by Grampp et al. (2000). The measurement system uses insoles consisting of 99 capacitive sensors which are sampled at 50 Hz. Data was collected from the last 20 seconds at each gradient condition while participants walked. As the treadmill gradient increased, loading (peak pressure PP and peak force PF) increased in the hallux and 1st metatarsal regions and decreased in the heel region. With negative gradients, loading (PP and PF) increased in the heel region and decreased in the 4th and 5th metatarsal regions.

2- On the muscle activity of the lower extremities' joints:

The phasic activity of the lower extremity muscles during up and down slope walking of 3, 6, 9 and 12 degrees was studied by Tokuhiro et al. (1985). Five muscles of ten healthy men were examined by electromyography, the muscles were the tibialis anterior (TA), gastrocenemius (GC), rectus femoris (RF), semitendinosus (ST) and gluteus maximus (GM). They found that during up slope walking the TA was not active during push off phase in 3 degree however it contracted in 6, 9 and 12 degrees and the GC increased its activity to elevate the body more in upslope walking than in level walking. Although the activity of the RF was observed in the latter half of swing phase in level and 3 and 6 degrees up slope walking, it was not seen in 9 and 12 degrees.

They also found that the (ST) showed activity from the latter half of swing phase to toe off in 6, 9 and 12 degrees and the activity of GM was prolonged in upslope walking compared to level walking. The steeper the slope became the more the hip joint flexed at heel strike, and the more GM contraction was required to elevate the body weight. In 6, 9 and 12 degrees down slope walking, the GC contraction earlier than in level walking appearing during heel contact. In contrast the TA showed the same activity in down slope walking as in level walking. Thus during heel contact the GC and TA showed synergistic contraction. The activity of the RF was observed during push off in down slope walking and the (ST) showed activity at the latter half of the swing phase to assist the RF in stabilization of the knee joint. The GM showed the nearly the same pattern of contraction in down slope as in level walking as the hip joint flexed less in down slope walking than in up slope.

The lower extremity muscle activation by using exercise-induced contrast shifts in magnetic resonance images during horizontal and uphill high-intensity (115% of peak oxygen uptake) running to exhaustion (2.0–3.9 min) in 12 young women was studied by Sloniger et al. (1997). They found that the mean percentage of muscle volume activated in the right lower extremity was greater during uphill than during horizontal running.

During horizontal running, the muscles most activated were the adductors, semitendinosus, gracilis, biceps femoris, and semimembranosus. While during uphill running, the muscles most activated were the adductors, biceps femoris, gluteal group, gastrocnemius, and vastus group. Compared with horizontal running, uphill running required greater activation of the vastus group (23%) and soleus (14%) and less activation of the rectus femoris (29%), gracilis (18%), and semitendinosus (17%). They concluded that during high-intensity horizontal and uphill running to exhaustion, lasting 2–3 min, muscles of the lower extremity are not maximally activated, suggesting there is a limit to the extent to which additional muscle mass recruitment can be utilized to meet the demand for force and energy.

It was also reported by Andrea et al. (2005) that during down slope walking the GC showed a significant reduction in mean activity and the RF and TA showed increases in mean activity levels as the walking grade changed from 0º to 39º. During stance phase of up slope walking the mean activity of the RF increased significantly as the walking grade increased and the activity of the GM at 15º and of the TA at 15º and 39º also increased.

3- On the moments of the lower extremities' joints:

The internal moments generated by the lower extremities joints during walking at different terrain varied significantly compared to level walking (Redfern et al. 2001). Walking down a ramp is accompanied by lowering of the body weight which required a strong knee extensor moment and the ankle demonstrated a large PF moment that peaks early during stance 1.4 Nm/Kg. Meanwhile, the hip demonstrated a relatively small extensor moment peaking 0.2 Nm/Kg at loading response phase (Andriacchi et al. 1980). It was reported by Redfern et al. (2001) that the ankle DF moment assumed a greater value while walking down a ramp of 0º, 5º, 10º, and 20º compared to walking on a level surface as its value increased with an increase in the ramp angle.

It was also reported by Andrea et al. (2005) that there was an increase in the knee joint moment and power during walking down a ramp of 0º, 15º and 39º. As shown in Figure (21) during level walking the GRF passes near the knee joint center and the associated joint moment should therefore be relatively small. While the knee is more flexed during down ramp walking and the GRF vector is directed posterior to it this would cause a large flexor moment to be applied at the knee joint, requiring the lower limb muscles to produce a large knee extensor moment to counteract the effect. The large knee extensor moment during down ramp walking results in more power generation than during level walking (fig. 22). Therefore, it was reported by McFadyen and Winter (1997) that the knee performs vital roles in the lowering of the body over the support foot via lengthening contractions of the extensors muscles. A similar change in the knee joint moment patterns has also been observed during stair descent (McFadyen and Winter 1988 and Riener et al. 2002). They reported that the stance phase knee joint moment has the same double-hump shape as the knee is flexed during stair descent to lower the body down the steps, and therefore power is absorbed at the knee.

Andrea et al. (2005) also observed that the ankle joint peak dorsiflexor moment in early stance increased uniformly during down ramp walking (AM1). The most noticeable change in the ankle moment was the progressive and significant decrease in the peak magnitude (AM2) as the ramp grade decreased from 0º to 39º (fig. 23).

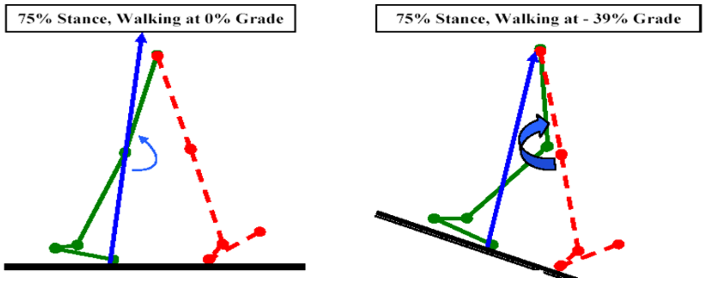


Fig. 21: The orientation of the GRF vector during walking down at 0º & 39º grades. (Adapted from Andrea et al. 2005).

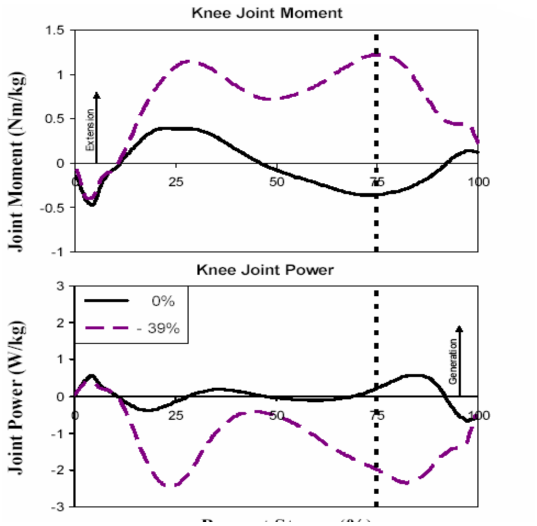


Fig. 22: The significant increase in the knee joint moment and power during walking down a ramp. (Adapted from Andrea et al. 2005).

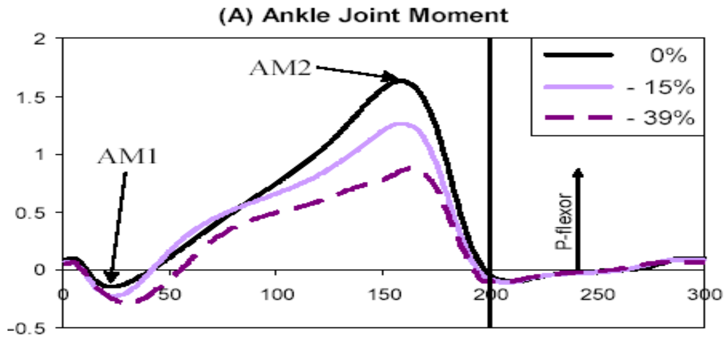


Fig. 23: Ankle moment during walking down a ramp. (Adapted from Andrea et al. 2005).

Elevation of the body during walking up a ramp was accomplished through large hip and knee extensor moments which peak during early stance reaching 1 Nm/Kg **(**Winter 1983 and Saibene and Minetti 2003). Andrea et al. (2005) also reported by that there was an increase in the hip joint moment and power during walking up a ramp of 0º, 15º and 39º. As shown in figure (24) during level walking the GRF passes near the hip joint centre, which as a first approximation would cause a small applied flexor moment (thin curved arrow). The associated internal joint moment should therefore be a relatively small extensor moment.

During upslope walking, however, the GRF vector is directed anterior to the hip joint centre, resulting in a larger applied hip flexor moment (thick curved arrow). This, in turn, would require a larger hip extensor moment during upslope walking. The large hip extensor moment during upslope walking results in more power generation than during level walking (fig. 25). Therefore, it was reported by Riener et al. (2002) that during upslope walking the hip extensors are the primary sources of propulsion, while the knee extensors performed this role during walking up stairs. Andrea et al. (2005) also reported that the peak ankle plantarflexor moment (AM2) increased uniformly during upslope walking (fig. 26).

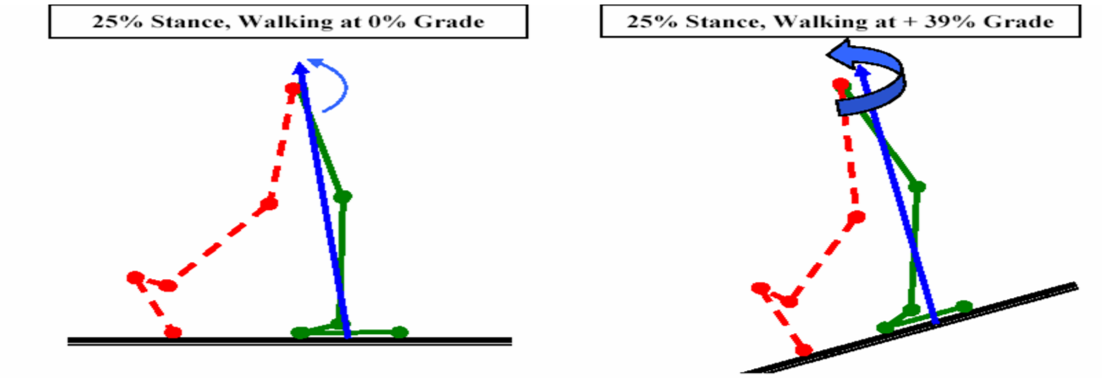


Fig. 24: The orientation of the GRF vector during walking up at 0º & 39º grades. (Adapted from Andrea et al. 2005).

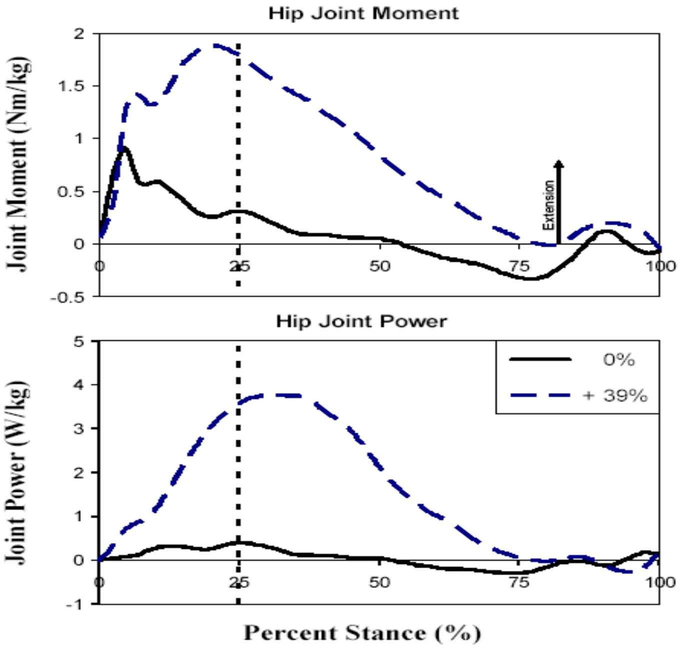


Fig. 25: The significant increase in the hip joint extensor moment and power during walking up a ramp. (Adapted from Andrea et al. 2005).

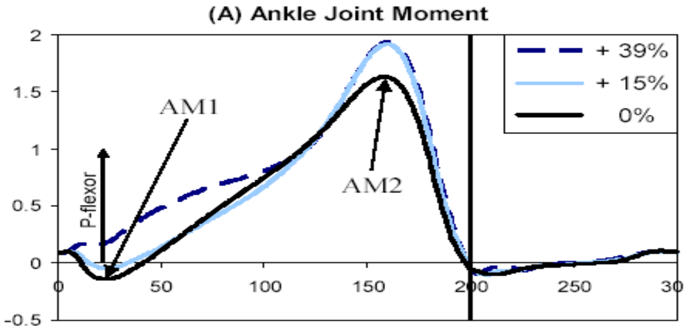


Fig. 26: Ankle moment during walking up a ramp. (Adapted from Andrea et al. 2005).

The kinetic of uphill running was studied by Thomas et al. (2005). They measured joint moment, power and work per step at the ankle, knee and hip joints using inverse dynamics calculation during moderate speed running at 0º, 6º, and 12º inclines. Their results revealed that the ankle function during incline running was very similar to that of level running and the net mechanical work developed at the ankle during stance was positive for all inclines (fig. 27).

They also found that the most of the work necessary to propel a runner uphill is produced by the hip muscles and represent 75% of the net work performed the knee and ankle muscles. The significant increase of the work produced at the hip joint may be attributed to an increase in the distance from the GRF to the hip joint center of rotation which associated with higher moment and increased in the work out put during running.

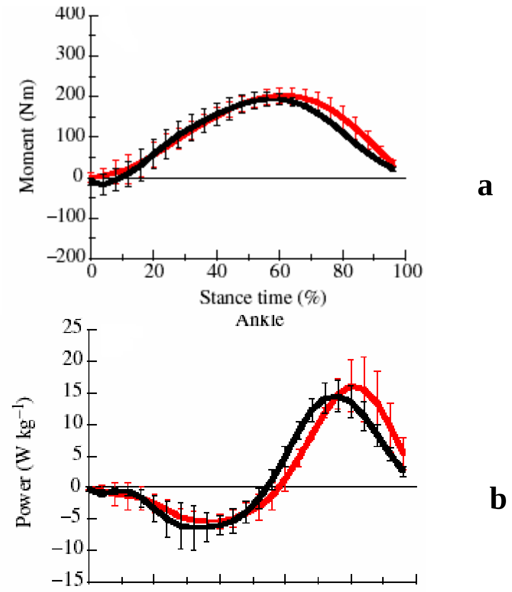


Fig. 27: Ankle power output (a) and moment (b) for stance during level running (black lines) and running on a 12° incline. (Adapted from Thomas et al. 2005).

4- On the angular displacement of the ankle joint:

Getchell and Whitall (1997) analyzed the active motion across the ankle complex (combined talocrural joint and subtalar joint) during walking on a level surface. They found that the range of inversion exceeds that of eversion by nearly the double: (22.6º for inversion versus 12.5º for eversion). The maximum range of abduction and adduction is nearly equivalent. Additionally, Hanna et al. (2000) observed that most of the motion of the rearfoot and forefoot occurred at the beginning and the end of stance phase.

Several studies have been performed on the stair climbing kinematics for healthy subjects. Results of Nadeau et al. (2003) showed that the angular displacement of the ankle joint in the frontal plane is not different from level ground walking. However, in the sagittal plane it was reported by Riener et al. (2002) that the stair climbing task involved a higher range of joint motion at the ankle. Therefore, it was reported by Power et al. (1997) that during stair ascending at the heel contact the ankle was in about 10 degree of dorsiflexion to permit tibial progression and accommodate the increased requirement of the knee flexion while the motion of the ankle joint in the swing phase was similar to that of level walking.

They also reported that during stair descending as the foot contact the ground the ankle was in 20º of plantar flexion. While a progressive ankle dorsiflexion was evident throughout the stance phase reaching 15º by 50% of the gait cycle and a plantar flexed ankle was observed during swing phase.

It was studied by Andrea et al. (2005) the angular displacement of the ankle joint during down ramp walking of 0º, 15º and 39º. They found that the ankle joint had a similar pattern to the level walking joint angles, but the peak magnitudes changed: the early stance peak plantarflexion angle (AA2) in figure (28) increased progressively and the swing phase peak plantarflexion angle (AA3) decreased progressively with the decreasing walking grade (figure 28).

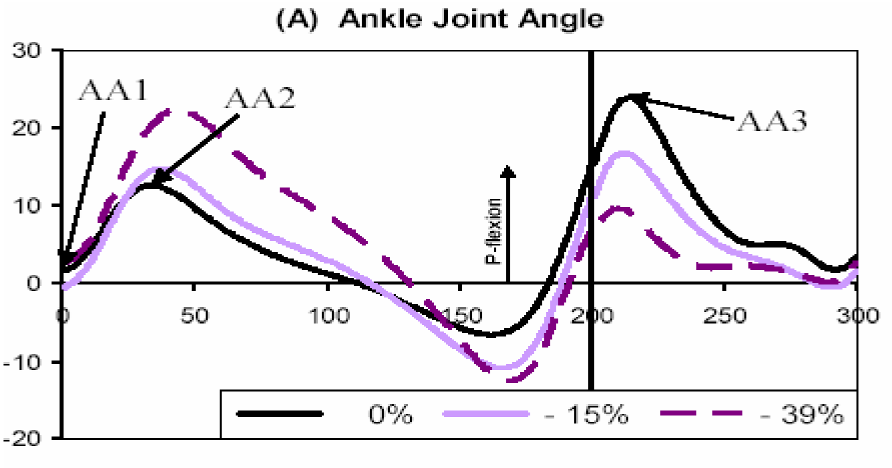


Fig. 28: Angular displacement of the ankle joint during walking down a ramp. (Adapted from Andrea et al. 2005).

It was also studied by Leroux et al. (2002) the angular excursions of the hip, knee and ankle joints during uphill and downhill walking of 0°, 5° and 10°. They found that walking upslope required an increased flexion from the three lower limb joints from mid-swing to early stance. This increase in flexion augmented progressively as the slope went steeper. Furthermore, the increase in hip flexion at the end of the swing phase might have contributed to the increase in stride length observed in uphill walking. While during downhill walking the hip joint showed a progressive decrease in flexion from mid-swing to early stance as the slope went down. At the knee joint, there was a progressive flexion in early stance during loading response and also in late stance while at the ankle joint no important changes were observed in downhill conditions.

The angular displacement of the ankle joint of the prosthetic foot was studied by Ragnarsdottir (2005). They reported that the widely used solid cushion heel (SCH) foot provided no ankle movement whereas the higher technology carbon foot products such as a flex range of motion foot provide an improved range of ankle motion.

Therefore, it was reported by Barth et al. (1992) that the increased ankle of the prosthetic foot involved an increased dorsiflexion angle for stair climbing and inclines walking. While for a decline walking a slight plantar flexion angle could be of benefit to improve the user's stability as it was reported by Testsuro et al. (2005) that there was a direct relationship between the passive ankle plantar flexion moment produced by connective tissues and the plantar flexion angle of the ankle joint during walking which was necessary to maintain its stability.

5- On the postural adaptation to walking on inclined surfaces

The control of the pelvis and trunk is important to achieve smooth locomotion and maintain body equilibrium during gait (Perry 1992). Therefore, it was studied by Leroux et al. (2001) the postural strategies to adapt to uphill and downhill treadmill inclination (0, 5 and 10%) during walking and standing in eight healthy subjects. The increase in the treadmill grade from 0 to 10% induced a progressive forward tilt of pelvis and trunk. These postural changes were accompanied by both a progressive decrease in pelvic lateral drop towards the swinging limb and a gradual increase in stride length as the uphill slope became steeper. Decreasing the treadmill grade from 0 to −10% led to both a gradual decrease in stride length, a progressive backward tilt of trunk and pelvis and an increase in pelvic lateral drop towards the swinging limb as downhill slope became steeper. Any changes in trunk and pelvic postural alignment in the sagittal plane might be used to facilitate power generation or absorption to adapt to ramp changes during walking (fig. 29). During quiet standing, however, the trunk and pelvis remained aligned with respect to earth’s vertical at any surface inclination. These results showed that postural adaptations are task-specific and the control requirements are different between standing and walking on an inclined surface.

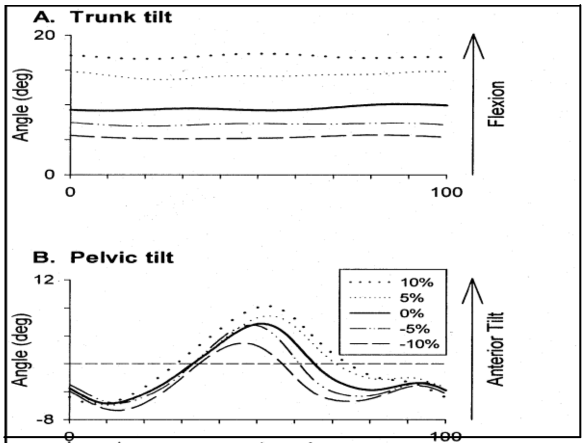


Fig. 29: Trunk and pelvic tilts during uphill and downhill walking in the normal subjects. (Adapted from Leroux et al. 2002).

It was also studied by Fung et al. (2006) the postural adaptation to walking on inclined surfaces, following spinal cord injury. Eight subjects with an incomplete spinal cord injury and sex-matched healthy control subjects walked on a treadmill at five different grades (-10, -5, 0, 5, and 10%) without any assistance. The movements of the trunk and pelvis were recorded. They found that the spinal cord injury subjects (SCI) walked with greater forward tilt of both trunk and pelvic segments during level or inclined walking and could not adapt their body orientation to the inclination of the support surface as observed in healthy control subjects. Trunk and pelvic rotations as well as lateral excursions were maintained constant during inclined walking in both groups of subjects, but total excursions were always greater in the (SCI) subjects (fig. 30).

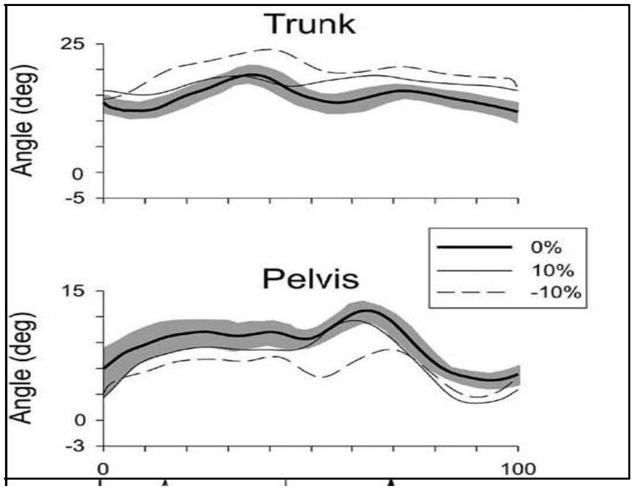


Fig. 30: Trunk and pelvic tilts during level and inclined walking in the (SCI) subjects. (Adapted from Fung et al. 2006).

Stability of the head-in-space establishes a stable platform to optimize sensitivity of visual and vestibular systems (Keshner et al. 1992). The changes in body orientation with respect to space during inclined walking on eleven young adults who walked along a level walkway, ascent and descent an inclined surface of 0°, 5°, 10° and 15° were studied by Cromwell (2003). They found that during both ascending and descending the inclined surface, the head orientation was maintained at a greater degree of flexion than the case during a level walking condition. In addition, the neck and trunk orientations were more flexed during descending the inclined surface only.

Related Literature:

Slope walking has been studied in a range of animal species, such as horses, rats, lizards and cats (Kuster et al. 1995, Daley and Biewener 2003 and Hooper et al. 2004). Many of these studies have investigated basic properties of muscles during slope walking. In cats, slope walking has been used to investigate neural control, and several studies have reported patterns of neuromuscular response that are different from those observed during level walking (Gravel et al. 1999).

Prilutsky et al. (1996) have used the adult cat in both treadmill and over-ground studies, and have reported unique muscle firing patterns. For example, hip flexor (iliopsoas) activity has been observed during the stance phase of downslope walking, when hip extensor activity normally occurs during level walking. In addition, unexpected hamstring activity occurred during stance in upslope walking. It was also reported by Carrier et al. (1998) the biomechanics of walking up a slope from 25% to 100% of normal cats and compared with similar data for level treadmill walking. They found that each cat assumed a crouched posture at the steeper grade of up slope walking and found that the range of ankle and knee joints extension increased.

The understanding of motor control can further be increased when EMG and kinetic data are combined. It was reported by Hreljac (1993) that the soleus appears to be the primary muscle contributing to the plantarflexor moment during quadruped down slope walking. In contrast, for upslope walking the soleus force decreases in spite of an increased plantarflexor moment (Kuster et al. 1995). Hreljac (1993) found that an increased the ankle plantarflexor and the knee flexor moments during the stance phase of upslope walking favor the activation of the two-joint gastrocnemius over the single-joint soleus. On the other hand, during downslope walking the joint moment demands (increased knee flexor and decreased plantarflexor moments) do not favor the activation of the gastrocnemius over the soleus.

It was also studied by John et al. (2004) the characterization of in vivo achilles tendon forces in rabbit during treadmill locomotion at varying speeds (0.1 and 0.3 mph) and inclination (0º and 12º). Implanted force transducers (IFT) were inserted in the medial and lateral heads of the left gastrocenemius tendon in 11 rabbits. Their results revealed that the peak force and the rates of rise and fall in the plantar flexor force significantly increased with an increase in the treadmill inclination.

A recently discovered locomotor behavior, wing-assisted incline running (WAIR) was studied by Lawrence and Grace (2004). WAIR allows fully animals to `run' up vertical obstacles. Such a task would appear to be especially formidable for bipeds. Four wild-type, captive bred, adult chukar partridges Alectoris were obtained from a local dealer. Birds were trained to ascend an inclined treadmill, the speed of which was selected to slow but not eliminate the animal's rate of climb. The birds were also trained to run up a ramp housing a force platform that could be inclined at angles between horizontal and vertical. The obtained results revealed that the mean values of peak ground reaction force (GRF) were all greater than those generated during fast level walks. These results indicate that at all of the experimental inclines, including the vertical, chukars were able to generate large forces against the substrate.

Materials and Methods

This study was carried out to investigate the effect of three different walking slopes on the magnitude of the vertical ground reaction force (GRF), the plantar flexion and dorsiflexion moments and the angular displacement of the right ankle joint during walking. The study was conducted at the Biomechanical Lab.at the Faculty of Physical Therapy, Cairo University. The practical part of this study lasted for one year. A group of 30 male university students participated in this study. They were instructed to walk over the force platform using three different walking ramps (5°- 10°- 15°) in two different positions. In the first position, the right leg was placed on a ramp over the force platform and the left leg was placed on another ramp of the same degree placed at a distance to the left of the first one. This position is referred to as right foot inclination, left foot inclination (RFI, LFI). While in the second position, the right leg was placed on the force platform without a ramp and the left leg was placed on a ramp. This position is referred to as right foot horizontal, left foot inclination (RFH, LFI).

Subject selection

Thirty male university students volunteered to participate in this study. All students were in good health and met the following criteria:

-Age: ranging from 18-22 years old.

-Height: ranging from 162-188 cm.

-Weight: ranging from 55-85 kg.

-Free from any musculoskeletal problems.

Instrumentation:

1- Recording data sheet

All data and information of each student were recorded on a recording data sheet (Appendix).

2- The walking ramp:

Two types of walking ramps of 5°-10°-15° were used in this study. The first type was placed over the force platform figure (31) while the second was placed to the left side of the first during walking (fig. 32). They were made of wood and had the following dimensions:

Dimensions of the first ramp (fig. 30)

Its length was 56 cm and its width was 35 cm.

Dimensions of the second ramp (fig. 31)

Its length was 1 m and its width was 25 cm.

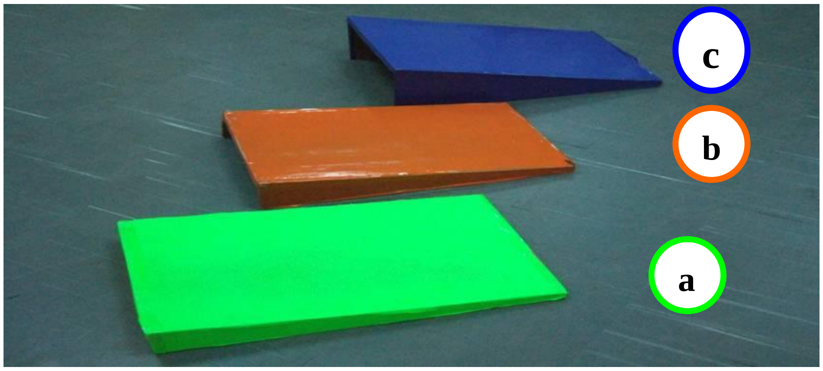


Fig. 31: The first type of the walking ramp; (a) 5 degrees, (b) 10 degrees and (c) 15 degrees.

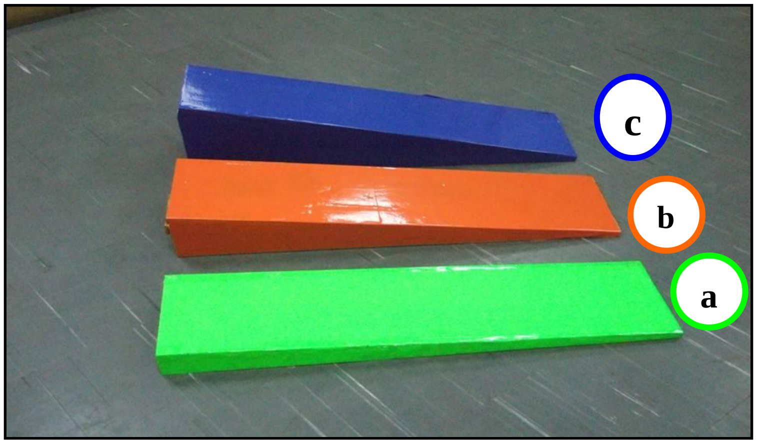


Fig. 32: The second type of the walking ramp; (a) 5 degrees, (b) 10 degrees and (c) 15 degrees.

3- Motion analysis system with a force plate unit

Three dimensional motion analysis system (Qualysis motion capture system) was used in this study in conjunction with a force plate unit to measure the kinetic and kinematic data. These data involve the magnitude of the vertical GRF, the ankle moments and the angular displacement of the right ankle joint during walking up three slopes (5°- 10°- 15°) at two different positions. The system consists of the following units:

a- Motion Capture Unit (MCU)

The unit consists of six infrared high speed Pro Reflex cameras. Each camera is held in its place on a tripod stand. The cameras' position can be adjusted easily on the tripod stand to track the marker position before capturing. The basic principal is to expose reflective markers to infra-red light emitted from the cameras and to detect the light reflected by the markers. The camera system is composed of six cameras to carry out multi camera measurements. The 2-D data from each camera in such system is retrieved simultaneously. The 2-D data from the six cameras are combined for calculating the 3-D position of the markers. All cameras have a capture capability of 120 frame/seconds. A master camera (camera number 1) is responsible for collecting all data from the other five cameras and transmitting them to the computer unit for further analysis.

b- The force plate unit

An AMTI (Advanced Mechanical Technology Inc., USA) force plate is impeded in the centre of a walkway. Its dimensions are 40 cm in width and 60 cm in length. The sampling rate of the plate is 120Hz. It incorporates four strain gauge transducers situated at the four corners of the plate. These four transducers record force-time data in three planes during the activity. A long cable connects the force plate to a computer unit. The signals from the plate are first amplified by an internal amplifier and fed to an analogue to digital information (numbers) by the A/D converter. Thus, the final output of the system is the digitization voltage values.

The AMTI force plate uses a coordinate oriented system in the calculation of the GRF magnitude and moment. In such a system, the force exerted by the human body on the plate is to be measured and analyzed. This system is capable of measuring the three components of the GRF in the three axes. The first component is the reaction force in the anteroposterior axis (Rx), the second component is the reaction force in the mediolateral axis (Ry), while the third component is the reaction force in the vertical axis (Rz). Figure (33) shows the biomechanical lab. Which include the placement of the cameras in relation to the walkway and the force plate position in the center of the walkway.

Fig. 33: Placement of the cameras in relation to the force platform. (a) The cameras′ placement. (b) The position of the forceplate in the centre of the walkway.

c- Reflective markers

Twenty passive reflective markers were used in this study. They were silver in colour and of 30 mm surface area. These markers were adhered to the bony landmarkes using double face adhesive tapes (fig. 34).

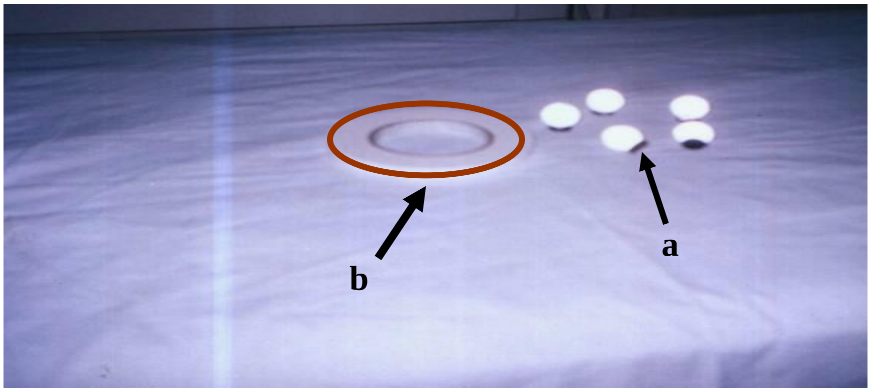


Fig. 34: The reflective markers (a) and the adhesive tapes (b) used to fix the markers.

d- Qualysis motion capture software

A personal computer with its accompanying softwares was used for data capturing and analysis. The softwares consists of three programs; Q trac, Q view and Q gait. The Q trac software is used to capture the 3D motion of the segments or body parts. The time of capture should be fed into the software. After capture, the software processes data immediately and gives the 3D data of each marker position. The Q view software is used to view the captured data after processing. Then it is used to identify the names of the markers and to export the identified marker names as TSV format (Tab Separated Values). Finally, the Q gait software enables the exported data format (data. TSV) to be manipulated so that the angle can be measured and calculated in the 3 axes of motion, X, Y, and Z (fig. 35). The software provides an angle-time plot of the marker.

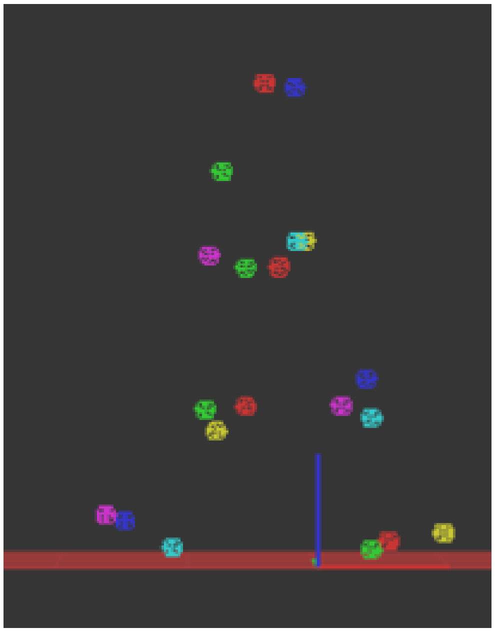


Fig. 35: The exported data format (data TSV).

e- A wand-kit, model number 130440

It was used for the calibration of the system. It provides the camera system with measurements points to be used for analysis so that the cameras can pick up as many markers as possible in the measurement volume X, Y, Z. The wand kit consists of two parts; a L-shaped part and a T-shaped part (fig. 36).

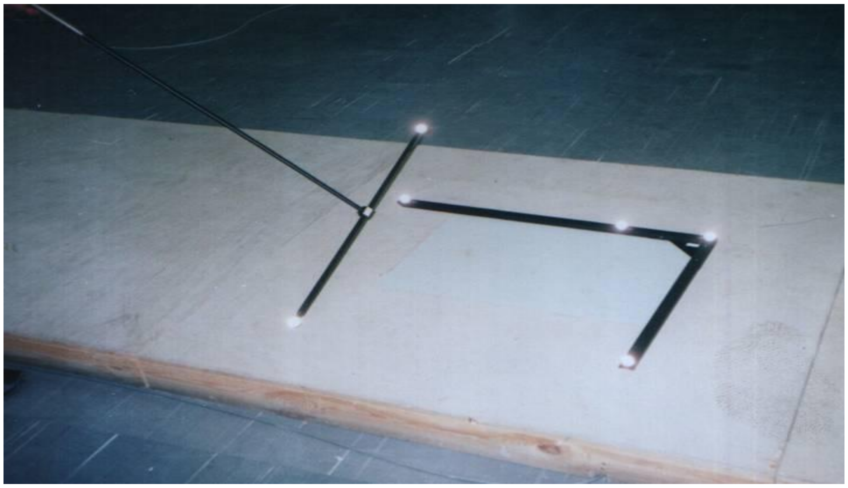


Fig. 36: A wand kit used for calibration of the system.

Testing procedures

The procedures of this study were divided into two phases

A- Preparatory phase.

B- Experimental phase.

a- Preparatory phase

It involved preparatory instructions, Qualysis Motion Capture System preparation and subject preparation.

1-Instruction

-Personal data involving the student׳s name and age were provided by the student before starting the study.

-Both the height and the weight were measured before starting the study.

-Each subject was allowed to use the walking ramp randomly among three different ones.

-Each subject was instructed carefully about the nature of the study and the task to be accomplished.

2-Qualysis Motion Capture System preparations

a- Calibration

As a preparation for the 3D motion capturing, the camera system was calibrated to detect the volume at which the cameras would pick up marker position. To achieve this, the wand kit was used which consisted of:

a- A reference structure (L- shaped kit) for defining the calibration coordinate system. This L shaped wand was lined by 4 markers and represented X and Y coordinates.

b- A wand kit (T- shaped) was used to provide the camera system with measurement points to be used for analysis. This wand was marked by 2 markers.

Calibration was set up at a volume of $2\times 1.5\times 6$ meters for all subjects. To set up the system for calibration, the following procedure was followed:

1- The L- shaped kit was placed horizontally along the floor in the measured volume.

2- It was assured that all cameras view all the four markers of the L- shaped kit.

3- Calibration was performed by pressing the capture button and moving the T wand around in the measurement volume in X, Y, and Z directions.

The force plate position was also calibrated. Four reflective markers were placed at the four corners of the plate. These markers identify the exact position of the force plate in space.

b- Capture

After calibration, the subjects were prepared for 3D measurement by placing twenty passive reflective markers on:

- Right and left shoulders.
- The 12th thoracic vertebrae.
- Sacrum.
- Right and left anterior superior iliac spines.
- Right and left greater trochanters.
- Right and left supra patellar regions.
- Right and left knee joints lines.
- Right and left tibial tuberosities.
- Right and left ankle joints.
- Right and left heels.
- Right and left toes (at the space between the 2nd and 3rd metatarsals).

Double- sided adhesive tape was used to attach the reflective markers to the skin at the recommended sites. Figure (37) presents the placement of the markers.

Fig. 37: The positioning of the twenty passive reflective markers.

3- Subject preparation

Each student was asked to stand bare-footed in front of the walk way. The walking ramps were matched to a randomized order for each student. Each student was asked to walk normally as much as possible and not to target on a slope during walking.

b- Experimental phase:

After placing the passive reflective markers on the skin at the recommended sites, the student were asked to walk along the walkway incorporates the force platform in two different positions:

- **The 1st position**

Two ramps of the same degree were used, one of them was placed on the force platform and the other was placed to the left side of the first one. During walking, the right leg of the student was placed on the first ramp, while the left leg was placed on the second one (fig. 38, 39 and 40).

Fig. 38: The first position with 5 degree walking ramp being used.

Fig. 39: The first position with 10 degree walking ramp being used.

Fig. 40: The first position with 15 degree walking ramp being used.

- **The 2nd position:**

In this position, the student was asked to place his right leg on the force platform without a ramp and the left leg was placed on a ramp to the left side of the platform (fig. 41, 42 and 43). Considering the motion capture, this was conducted for 8 seconds while the student was walking on the three tested walking ramps. The student was instructed to make three trials during walking on each ramp. The ankle dorsi/plantar flexion angles were recorded at the three trials.

Fig. 41: The second position with 5 degree walking ramp being used.

Fig. 42: The second position with 10 degree walking ramp being used.

Fig. 43: The second position with 15 degree walking ramp being used.

Data analysis:

1- Motion Analysis System data

The computer software was used to analyze the kinematics and kinetic parameters. The selected data (one complete gait cycle in addition to another 25%) of the following one was exported to another software (Q gait) using the TSV format (Tab Separated Values). The Q trac software was used to record the right ankle dorsi/plantar flexion angles.

2- Force platform data

Any force exerted on the force platform was transmitted through the force transducers. The synchronization between the force platform and motion analysis system enabled the measurement of the ground reaction forces, muscle moments and power in the three planes (X,Y,Z).

Statistical design

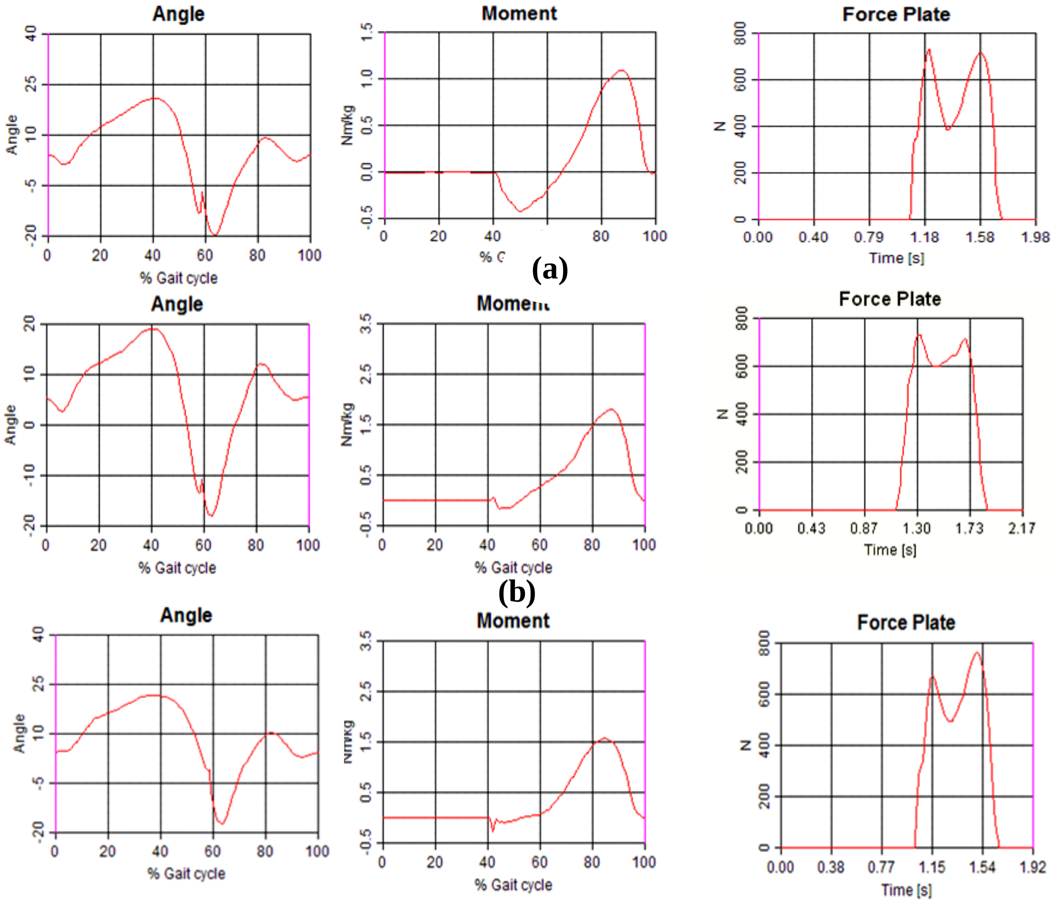
Data were analyzed through using (Repeated Measures) ANOVA for comparison among the three walking slopes at the two different positions.

Results

This study was conducted on thirty university students to investigate the effect of the three walking ramps (5º- 10º- 15º) on the vertical ground reaction force (GRF), right ankle plantar flexion (PF) / dorsiflexion (DF) moments and the angular displacement of the right ankle joint during walking (fig. 44). Two positions of walking slopes were involved in the study; the right foot inclination and the left foot inclination (RFI, LFI), and the second one was the right foot horizontal and the left foot inclination (RFH, LFI).

Repeated Measures ANOVA was used with the two peaks of GRF (F1, F3) as the first dependent variable and the right ankle PF/DF moments as the second dependent variable. The independent variables were the three angles of the walking slopes. Least significant difference (LSD) multiple comparison post hoc test was used to determine the significant difference between the mean values of the dependent variables at each position of the three walking slopes in addition to comparing the changes that occur in the dependent variables at each position.

A correlation test was used to compare each of F1 with DF moment and F3 with PF moment at each position of the three walking ramps. In addition, a paired t- test was used to compare between the first and the second positions. All statistical analysis tests were conducted through using SPSS for windows, version 8.0.0 (SPSS, Inc., Chicago, IL). The alpha level of significance was set at 0.05



(c)

Fig. 44: The results obtained from Q gait software during walking up the three ramps. (a) ramp of 5°, (b) ramp of 10°, and (c) ramp of 15°.

The first position

Right foot inclination, left foot inclination (RFI, LFI):

1- GRF variation:

a- Effect of the three walking ramps on the two peaks of the GRF during walking:

The results of the study showed that the mean value of F1 while walking up ramp of 5º, 10º and 15º inclinations was 104.9 (±6.2) % BW, 107.9 (±9.4) % BW and 106.3 (±7.5) % BW respectively. Meanwhile, the mean value of F3 was 110.7 (±6.4) % BW, 110.7 (±7.5) % BW and 110.4 (±7.7) % BW for the three tested ramps respectively.

For each of F1 and F3, statistical analysis revealed that there was no significant difference (P > 0.05) among the three tested walking ramps (5º, 10º and 15º). Meanwhile, paired comparison using the Least significant difference (LSD) multiple comparison post hoc test revealed that there was no significant difference (P> 0.05) between each of ramp of 5º and ramp of 10º, ramp of 5º and ramp of 15º and ramp of 10º and ramp of 15º for each of F1 and F3. Table (1) and figure (45) summarize the previous results.

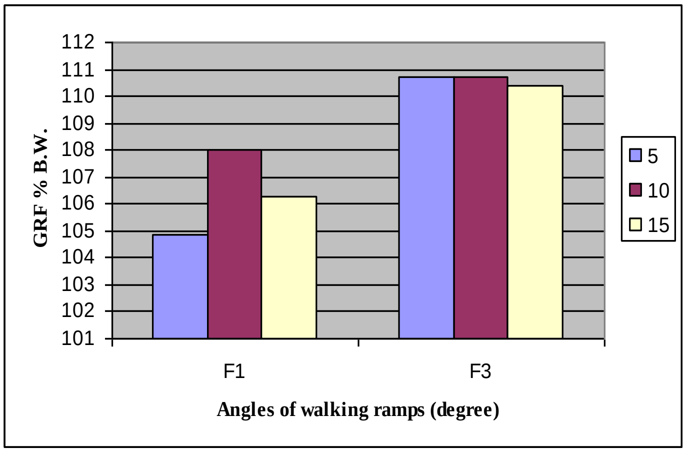
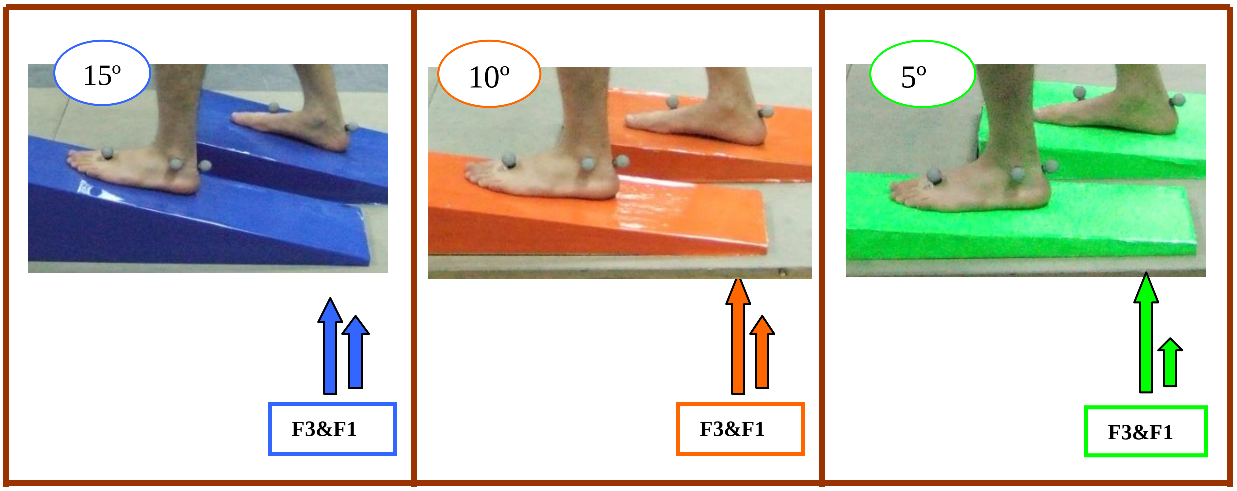


Fig. 45: F1 and F3 peaks of GRF in the first position (RFI, LFI) of the three walking ramps.

Table 1: Descriptive statistics and Repeated Measure ANOVA for the two peaks of the GRF while walking up the three tested ramp (5º, 10º, 15º) at the first position (RFI, LFI).

GRF						
	F1			F3		
ramp	5º	10º	15º	5º	10º	15º
X'± SD	104.9±6.2	107.9±9.4	106.3±7.6	110.7±6.4	110.7±7.5	110.4±7.7
Repeated Measure ANOVA						
F ratio	1.2			0.02		
P value	0.31			0.98		



2- Moment variation

a- Effect of the three walking ramps on the right ankle PF/DF moments during walking

The results of the study showed that the mean value of the right ankle PF moment was 1.4 (±0.2) Nm/Kg, 1.5 (±0.3) Nm/Kg and 1.51 (±0.2) Nm/ Kg while walking up ramps of 5º, 10º and 15º respectively. Meanwhile, the mean value of the right ankle DF moment was 0.04 (±3.6) Nm/Kg, 0.13 (±8.9) Nm/Kg and 0.06 (±3.9) Nm/Kg for these three tested ramps respectively.

Using the multiple comparison ANOVA test, a non significant difference was found among the three tested ramps for the PF moment. However, a significant difference was found for the DF moment. Meanwhile, the LSD multiple comparison post hoc test revealed that there was no significant difference (P > 0.05) between each ramp of 5º and ramp of 10º, ramp of 5º and ramp of 15º and ramp of 10º and ramp of 15º for the PF moment. In addition a significant difference was found between each of ramp of 5º and ramp of 10º and ramp of 10º and ramp of 15º for the DF moment (p < 0.05). However, a non significant difference was found between, ramp of 5º and ramp of 15º for the DF moment (P > 0.05) (Table 2 and figure 46).

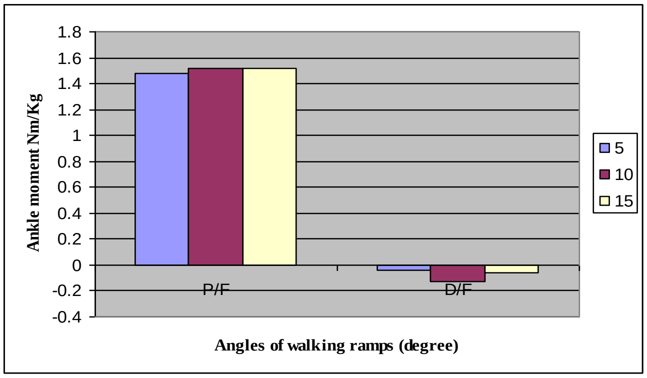
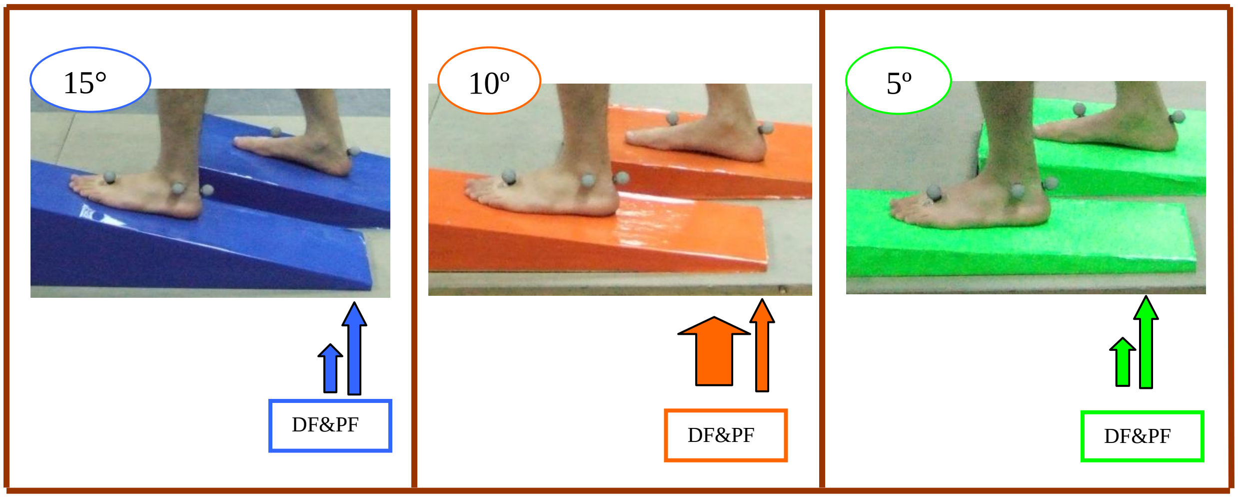


Fig. 46: Ankle PF and DF moments in the first position (RFI, LFI) of the three walking ramps.

Table 2: Descriptive statistics and Repeated Measure ANOVA for the plantarflexion/dorsiflexion moments while walking up the three tested ramps (5º, 10º, 15º) at the first position (RFI, LFI).

Moments						
ramp	Plantarflexion (PF)			Dorsiflexion (DF)		
	5º	10º	15º	5º	10º	15º
X'± SD	1.4±0.2	1.5±0.2	1.51±0.2	0.04±3.6	0.13±8.9	0.06±3.9
Repeated Measure ANOVA						
F ratio	0.4			16.6		
P value	0.7			0.000*		
LSD multiple comparison test (P-value)						
5 vs 10	P > 0.05			P < 0.05*		
5 vs 15	P > 0.05			P > 0.05		
10 vs 15	P > 0.05			P < 0.05*		



3- Relationship between the two peaks of the GRF and the ankle joint moments

The relationship between the mean values of the first peak of the GRF (F1) and ankle dorsiflexion moment (DF) in the first position was tested using a correlation test. Results revealed that there was no significant correlation ($P > 0.05$) between both of F1 and DF moment at a ramp of 5º ($r = 0.07$), ramp of 10º ($r = -0.36$) and at a ramp of 15º($r = -0.1$).

Meanwhile, the relationship between the mean values of the second peak of the GRF (F3) and ankle plantarflexion moment (PF) in the first position was also tested using a correlation test. Results revealed that there was a significant correlation ($P < 0.05$) between both of F3 and PF moment at a ramp of 5º ($r = .39$) and at a ramp of 10º ($r = .44$). However, there was no significant correlation at a ramp of 15º($r = 0.33$). Table (3) and figures (47& 48) summarize the previous results.

Table 3: correlation between each of F1 and the right ankle DF moment and F3 and the PF moment at the three walking ramps in the first position (RFI, LFI).

ramps	5º		10º		15º	
correlation test	P	r	P	r	P	r
F1 & DF	0.73	0.07	0.051	-0.36	0.6	-0.1
F3 & PF	0.03	.39*	0.015	.44*	0.072	0.33

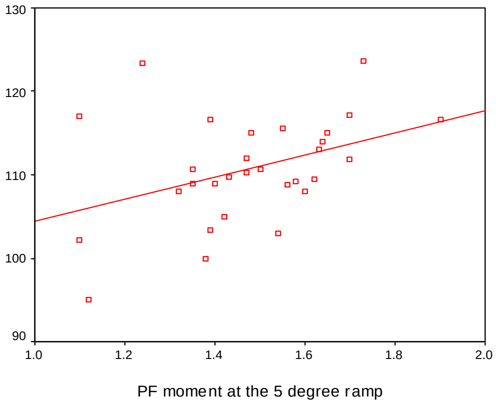


Fig. 47: Scatter diagram showing the correlation between the magnitude of F3 and the ankle PF moment at the 5 degree ramp in the first position.

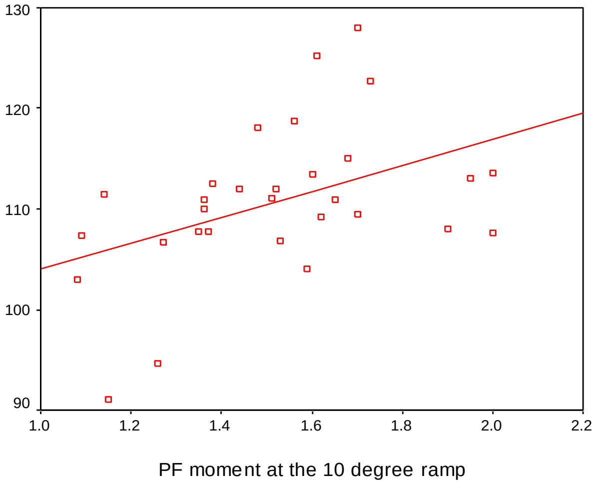


Fig. 48: Scatter diagram showing the correlation between the magnitude of F3 and the ankle PF moment at the 10 degree ramp in the first position.

The second position

Right leg horizontal, left leg angle inclination (RFH, LFI)

1- GRF variation

a- Effect of the three walking ramps on the two peaks of the GRF during walking

The mean value of F1 was found to be 108.3 (±6.6) % BW, 110.6 (±8.5) % BW and 107.4 (±7.7) % BW while walking up ramps of 5º, 10º and 15º respectively. While the mean value of F3 was found to be 116.7 (±9.1) % BW, 120.2 (±8.9) % BW and 122.2 (±10.1) % BW for these tested three ramps respectively.

Considering the difference among the three tested ramps (5º, 10º and 15º) for the magnitude of each of the two peaks of the GRF (F1 and F3), statistical analysis using Repeated Measures ANOVA revealed that there was no significant difference ($P > 0.05$). Meanwhile, LSD multiple comparison post hoc test revealed that there was only a significant difference between ramp of 5º and ramp of 15º for F3 ($P < 0.05$) with a non significant difference between any of the pair of ramps for each of F1 and F3 ($p > 0.05$) Table (4) and figure (49) summarize the above findings.

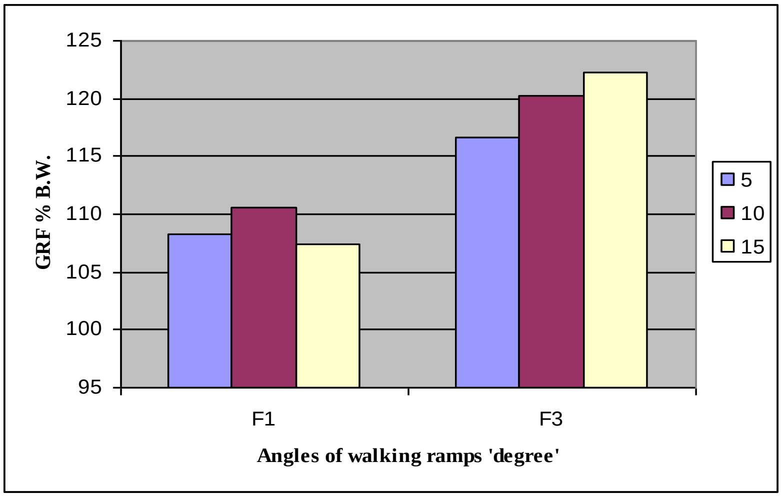
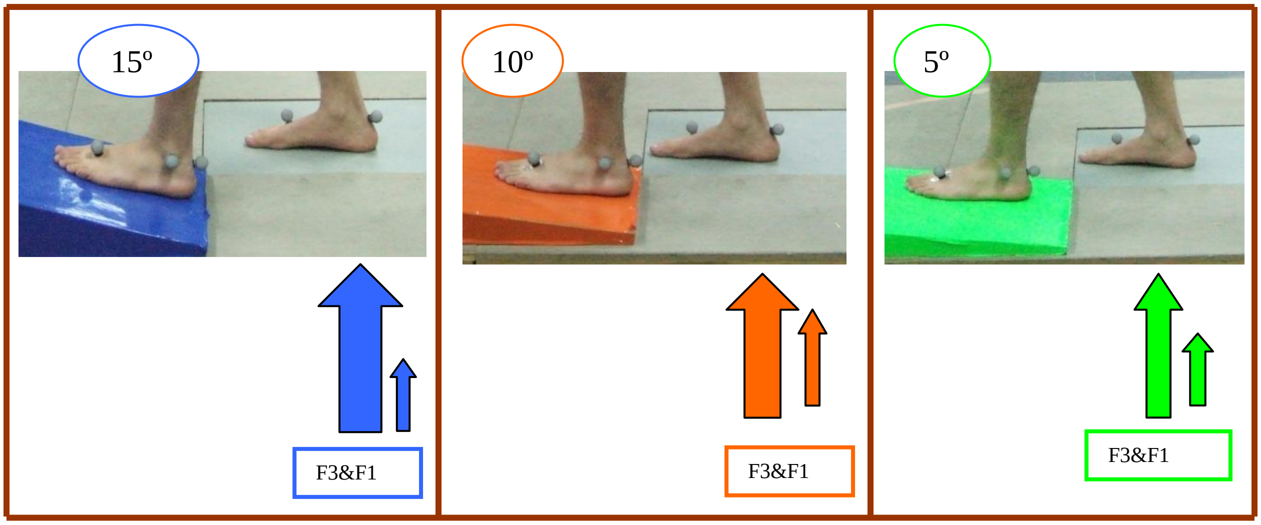


Fig. 49: F1 and F3 peaks of GRF in the second position (RFH, LFA) of the three walking ramps.

Table 4: Descriptive statistics and Repeated Measure ANOVA for the two peaks of the GRF while walking up the three tested ramp (5°, 10°, 15°) at the second position (RFH, LFI).

GRF						
	F1			F3		
ramp	5°	10°	15°	5°	10°	15°
X'±SD	108.3±6.6	110.6±8.5	107.4±7.7	116.7±9.1	120.2±8.94	122.±10.1
Repeated Measure ANOVA						
F ratio	1.4			2.6		
P value	0.3			0.08		
LSD multiple comparison test (p-value)						
5° vs10°	P > 0.05			P > 0.05		
5° vs15°	P > 0.05			P < 0.05*		
10°vs15°	P > 0.05			P > 0.05		



2- Moment variatio

a- Effect of the three walking ramps on the right ankle PF/DF moments during walking

The mean value of the ankle PF moment was found to be 1.5 (±0.2) Nm/Kg, 1.6 (±0.3) Nm/Kg and 1.6 (±0.2) Nm/Kg while walking up ramps of 5°, 10° and respectively. While, the mean value of the ankle DF moment was found to be 0.16 (±5.6) Nm/Kg, 0.17 (±6.7) and 0.17 (±5.3) Nm/Kg while walking up these three tested ramps.

Statistical analysis using Repeated Measures ANOVA revealed that the absence of any significant difference (P > 0.05) among the three tested walking ramps for each of the ankle PF and DF moments. Moreover, the LSD multiple comparison post hoc test revealed the absence of any significant difference (P > 0.05) between each of ramp of 5° and ramp of 10°, ramp of 5° and ramp of 15° and ramp of 10° and ramp of 15° for each of the ankle PF and DF moments Table (5) and figure (50) present the above findings.

Table 5: Descriptive statistics and Repeated Measure ANOVA for the plantarflexion/dorsiflexion moments while walking up the three tested ramps (5º, 10º, 15º) at the second position (RFH, LFI).

	Moments					
	Plantarflexion (PF)			Dorsiflexion (DF)		
ramp	5º	10º	15º	5º	10º	15º
X'± SD	1.5±0.2	1.6±0.3	1.6±0.2	0.2±5.6	0.2±6.7	0.2±5.3
	Repeated Measure ANOVA					
F ratio	2			0.05		
P value	0.13			0.9		

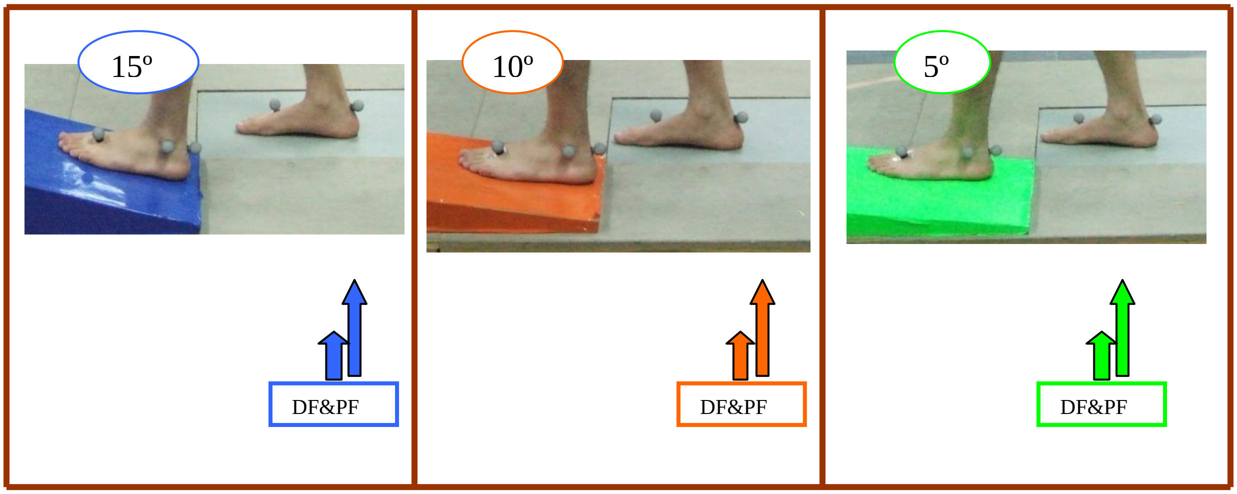


Fig. 50: Ankle PF and DF moments in the second position (RFH, LFI) of the three walking ramps

3- Relationship between the two peaks of the GRF and the ankle joint moments

The relationship between the mean values of the first peak of the GRF (F1) and ankle dorsiflexion moment (DF) in the second position was tested using a correlation test. Results revealed that there was no significant correlation ($P > 0.05$) between both of F1 and DF moment at a ramp of 5º ($r = - 0.2$), ramp of 10º ($r = -0.2$) and at a ramp of 15º($r = -0.2$).

Meanwhile, the relationship between the mean values of the second peak of the GRF (F3) and ankle plantarflexion moment (PF) in the second position was also tested using a correlation test. Results revealed that there was a significant correlation ($P < 0.05$) between both of F3 and PF moment at a ramp of 5º ($r = 0.4$) and at a ramp of 10º ($r = 0.5$). However, there was no significant correlation at a ramp of 15º($r = 0.3$). Table (6) and figures (51& 52) summarize the previous results.

Table 6: Correlation between each of F1 and the right ankle DF moment and F3 and the PF moment at the three walking ramps in the second position (RFH, LFI).

ramps	5º		10º		15º	
correlation test	P	r	P	r	P	r
F1 & DF	0.2	-0.3	0.3	-0.2	0.3	-0.2
F3 & PF	0.02	0.4*	0.01	0.5*	0.1	0.3

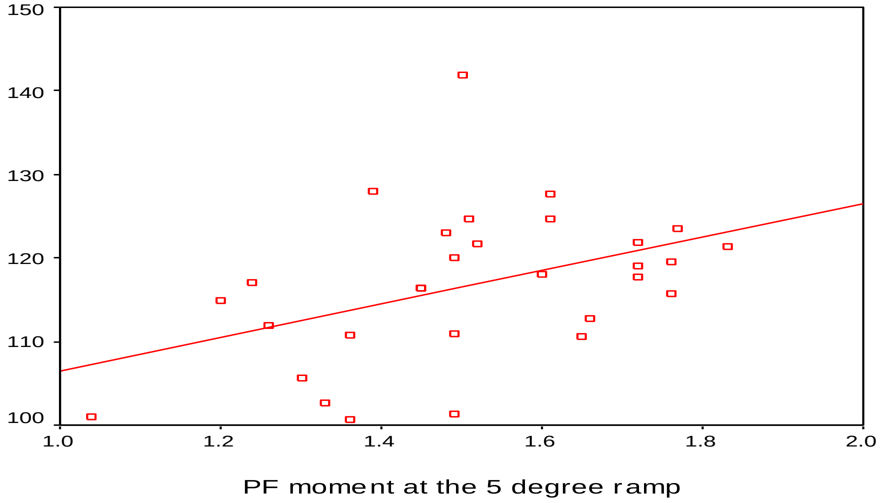


Fig. 51: Scatter diagram showing the correlation between the magnitude of F3 and the ankle PF moment at the 5 degree ramp in the second position.

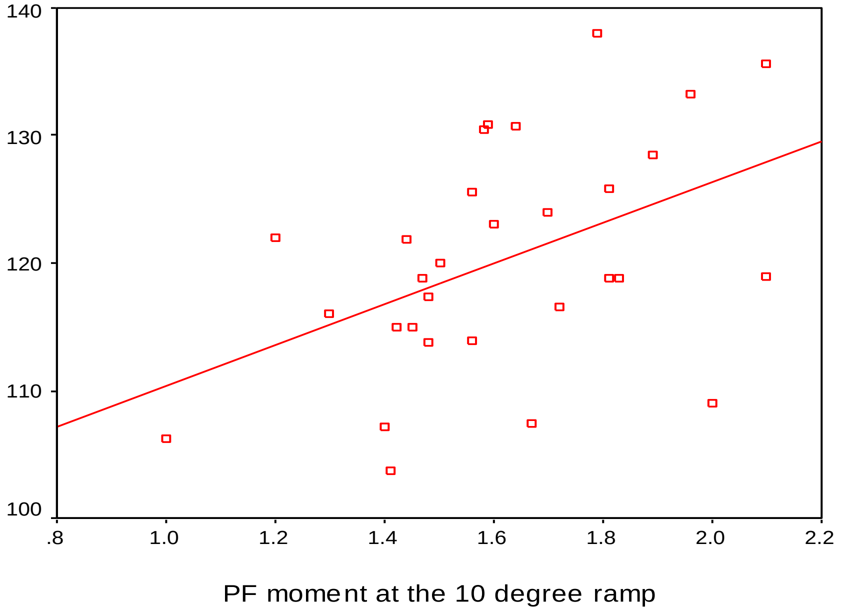


Fig. 52: Scatter diagram showing the correlation between the magnitude of F3 and the ankle PF moment at the 10 degree ramp in the second position.

- **Comparison between the first and second positions of walking ramps with regard to the mean value of the two peaks of GRF and ankle moments**

The two tested positions used in this study were illustrated as follow: In the first position, the right leg was placed on a ramp over the force platform and the left leg was placed on another ramp of the same degree placed at a distance to the left of the first one. While in the second position, the right leg was placed on the force platform without a ramp and the left leg was placed on a ramp.

1- GRF

The difference between the two tested positions for the mean value of each of the GRF peaks was statistically tested using paired t- test. Results revealed that there was a significant difference ($P < 0.05$) between both positions for F3 at each of a ramp of 5º, ramp of 10º and ramp of 15º. Meanwhile, no significant difference was found ($P > 0.05$) between both positions for F1 with the exception at a ramp of 5º as the P value was < 0.05 (fig. 53& 54) (Table 7).

Table 7: Paired t- test of the two peaks of the GRF between the first and the second positions.

	GRF					
	F1			F3		
ramp	5º	10º	15º	5º	10º	15º
T value	-2.1	-1.11	-0.6	-2.9	-4.4	-5.1
p value	0.02*	0.13	0.3	0.002*	0.000*	0.000*

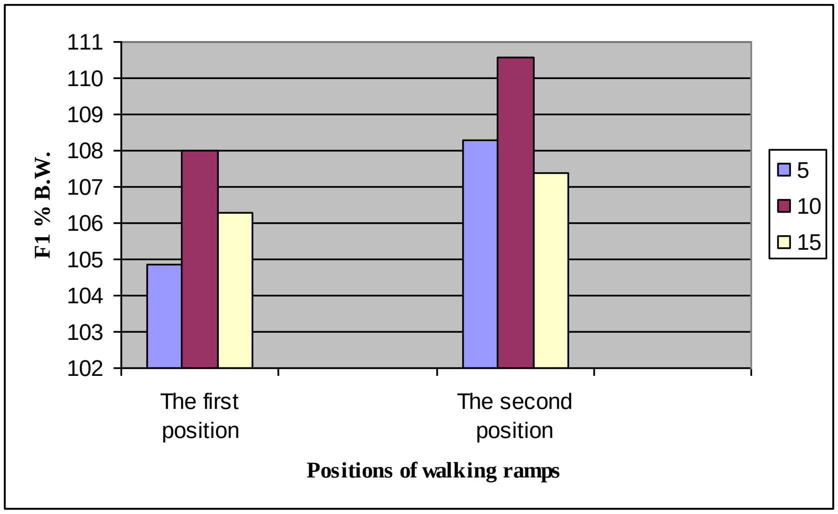


Fig. 53: The effect of the two positions of walking ramps on the mean values of F1.

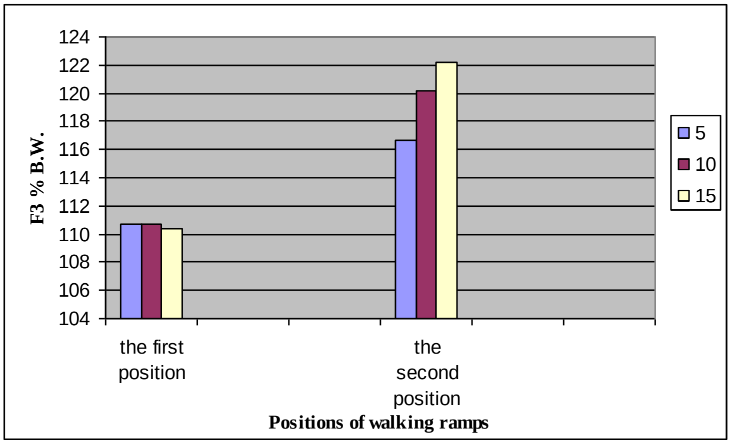


Fig. 54: The effect of the two positions of walking ramps on the mean values of F3.

2- Ankle moments:

Testing the difference between the two tested positions for the mean value of each of the ankle plantarflexion and dorsiflexion moments was conducted using paired t- test. Results revealed that there was no significant difference (P > 0.05) between both positions for each of the plantarflexion and dorsiflexion moments (table 8 & figure 55).

Table 8: Paired t- test of the ankle PF and DF moments between the first and the second positions.

	Moments					
	Plantarflexion (PF)			Dorsiflexion (DF)		
ramp	5º	10º	15º	5º	10º	15º
T value	-0.6	-1.4	-1.71	9.8	1.9	8.5
P value	0.2	0.07	0.05	1	0.96	1

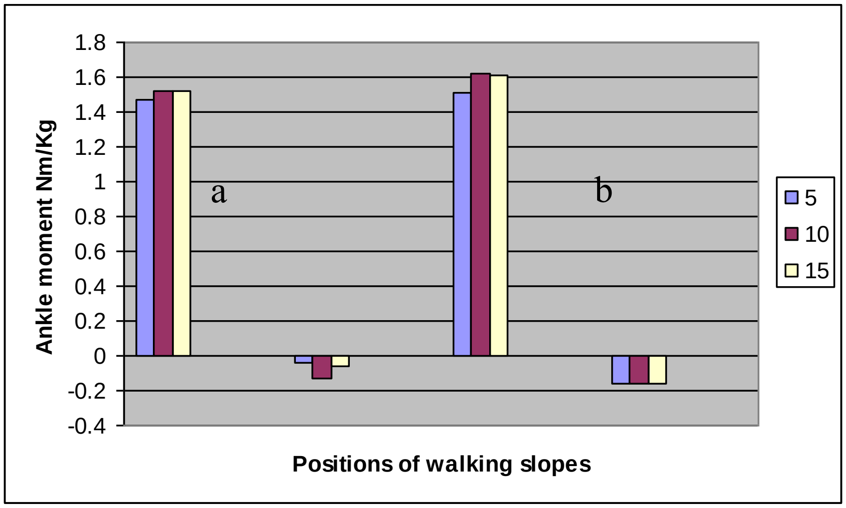


Fig. 55: The effect of the first (a) and the second (b) positions of walking ramps on the mean values of the ankle PF (positive values) & DF (negative values) moments.

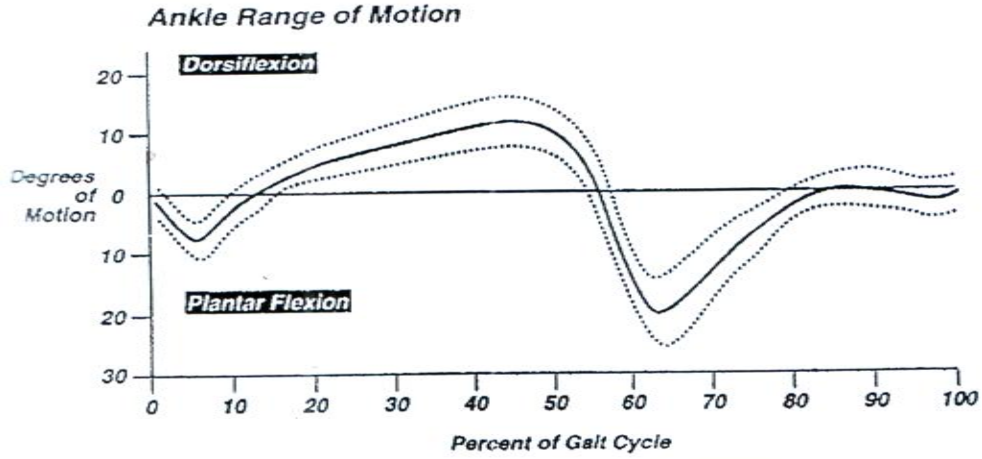
Kinematic analysis of gait

This study investigated the effect of using different walking slopes on the angular displacement of the right ankle joint throughout a gait cycle during walking. The range of motion of the ankle joint was recorded across the sagittal plane of motion (XZ) only (plantar flexion\dorsiflexion).

Analysis of the results demonstrated that using different walking slopes produced different angular displacements of the ankle joint. The effect of the walking slopes on the angular displacement of the ankle joint at each position is discussed below.

1- Ankle joint's ROM during walking on a level surface

In normal pattern of gait during each gait cycle, there are four arcs of ankle motion, two arcs of ankle plantar flexion (PF) and two arcs of ankle dorsiflexion (DF) (Fig. 56). The first three arcs of motion occur in stance phase. The first plantar flexion arc occurs at loading response phase as the foot is gradually lowered on the ground reaching about 15º. While the second arc of planterflexion occurs during the preswing phase reaching a range of 20º - 30º. Considering the arcs of dorsiflexion, the first arc occurs at the first half of the terminal stance reaching about 10º. During the swing phase there is only one dorsiflexion arc. It occurs during the mid swing phase with the ankle joint being in a neutral position (Oatis 2004).



Ankle motion during normal gait cycle.

Fig. 56: The ankle joint's ROM during walking on a level surface (Adapted from Oatis 2004).

2- Ankle joint's ROM during walking up a ramp

The pattern of gait during walking on a slope is different from walking on a level surface. This pattern is even different from one position to another at the three walking slopes (ramp of 5º, ramp of 10º and ramp of 15º).

- **Walking up a ramp of 5º**

The angular displacement of the right ankle joint was as follows

1- The first position (RFI, LFI) (fig. 57 a)

a- In stance phase

1- (0 - 30%) of the gait cycle

As the heel contact the ground, the ankle was found to be in a dorsiflexed position, the dorsiflexion angle increased gradually to reach 10º - 15º at the end of mid stance phase.

2- (30% - 65%) of the gait cycle

The ankle joint gradually moved towards plantar flexion to reach 10º - 15º at the end of the pre swing phase.

b- In swing phase

1- (65% - 87%) of the gait cycle

The plantar flexion decreased gradually and the ankle joint moved towards dorsiflexion (fig. 57 a).

2- (87% - 100%) of the gait cycle

The ankle assumed a dorsiflexed position.

2- The second position (RFH, LFI) (fig. 57 b)

a- In stance phase

1- (0 - 30%) of the gait cycle

At the beginning of the stance phase, the ankle moved towards plantar flexion then it changed its direction reaching 5º dorsiflexion at the end of mid stance.

2- (30% - 65%) of the gait cycle

The dorsiflexion decreased and the ankle moved in a plantar flexion direction at the end of the preswing phase.

b- In swing phase

The angular displacement of the ankle joint in the swing phase was nearly the same that of the first position (fig. 57 b). The observed difference between the first and the second positions while walking up a ramp of 5º was: At (0 - 10%) of the gait cycle, the ankle was dorsiflexed as the heel contacted the ground in the first position while it moved towards plantar flexion in the second one.

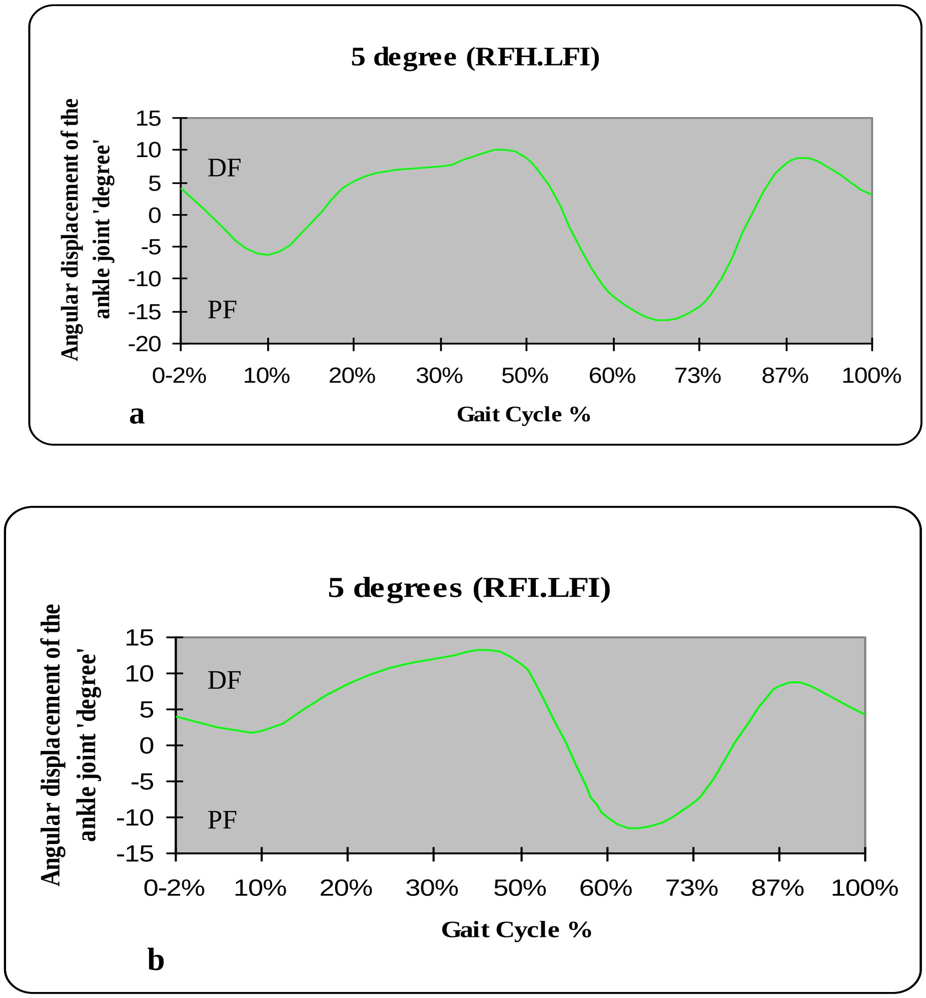


Fig. 57: Angular displacement of the ankle joint during walking up a ramp of 5º in the first (a) and the second (b) positions.

- **Walking up a ramp of 10º**

The angular displacement of the ankle joint was recorded as follows

1- The first position (RFI, LFI) (fig. 58 a)

a- In stance phase

1- (0 - 30%) of the gait cycle

The ankle was in a dorsiflexed position when the heel contacted the ground which gradually increased reaching 10º-15º at the end of mid stance.

2- (30% - 73%) of the gait cycle

The dorsiflexion decreased and the ankle moved towards plantar flexion.

b- In swing phase

1- (73% - 87%) of the gait cycle

The ankle plantar flexion increased reaching about 10º then the ankle gradually moved towards dorsiflexion at the end of mid swing (fig. 58 a).

2- (87% - 100%) of the gait cycle

The ankle remained in a dorsiflexed position.

2- The second position (RFH, LFI) (fig. 58 b)

a- In stance phase

1- (0 - 30%) of the gait cycle

The ankle moved towards plantar flexion when the heel contacted the ground then gradually changed its direction towards dorsiflexion at the end of mid stance.

2- (30% - 65%) of the gait cycle

The ankle gradually moved towards plantar flexion reaching 10º - 15ºat the end of pre swing.

b- In swing phase

The R.O.M of the ankle joint in the swing phase was nearly the same that of the first position (fig. 58 b). The observed difference between the first and the second positions while walking up a ramp of 10º was as follows

1-At (0- 10%) of the gait cycle: The dorsiflexion increased at the beginning of the stance phase in the first position reaching 5º dorsiflexion. While in the second position it reached 5º plantar flexion.

2- At pre swing phase: The ankle moved from dorsiflexion to plantar flexion in the first position at (73% of the gait cycle) while a gradual increase in plantar flexion occurred in the second position about 15º (at 65% of the gait cycle)

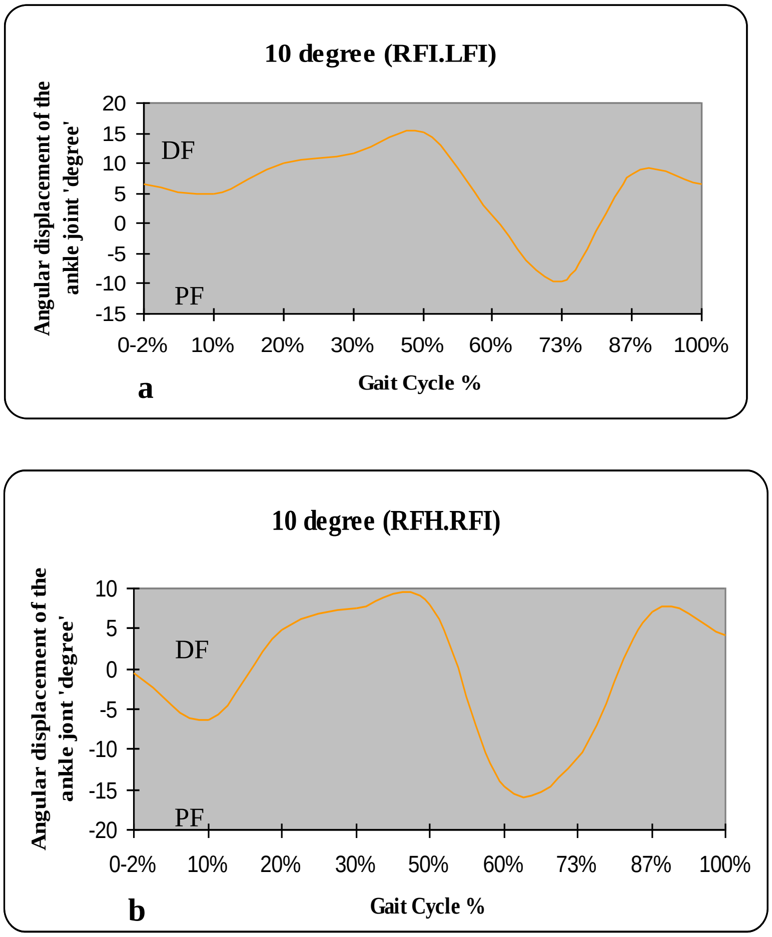


Fig. 58: Angular displacement of the ankle joint during walking up a ramp of 10º in the first (a) and second (b) positions.

- **Walking up a ramp of 15º**

The angular displacement of the right ankle joint while walking up a ramp of 15º was as follows

1- The first position (RFI, LFI) (fig. 59 a)

a- In stance phase

1- (0 - 30%) of the gait cycle

The heel contacted the ground with a dorsiflexed ankle joint. It remained in dorsiflexion with slight variations at the end of mid stance.

2- (30% - 73%) of the gait cycle

The planter flexion increased gradually reaching 10º -15º at 73% of the gait cycle.

b- In swing phase

1- (73% - 87%) of the gait cycle

The planter flexion decreased and the dorsiflexion increased gradually at the beginning of the swing phase (fig. 59 a).

2- (87% - 100%) of the gait cycle

Dorsiflexion of the ankle joint.

2- The second position (RFH, LFI) (fig. 59 b)

a- In stance phase

1- (0 - 30%) of the gait cycle

The ankle joint moved in a plantar flexion direction as the heel contacted the ground. While at the end of mid stance, it changed its direction to be dorsiflexion.

2- (30% - 65%) of the gait cycle

The ankle moved towards plantar flexion reaching 15º - 20º at the end of preswing.

b- In swing phase

The range of motion of the ankle joint was the same as that recorded at the first position (fig. 59 b). The observed differences between the first and the second positions while walking a ramp of 15º were 1-At (0- 10%) of the gait cycle: The heel contacted the ground with a dorsiflexed ankle joint in the first position and a plantar flexed ankle joint in the second position. 2- At pre swing phase: The ankle was dorsiflexed in the first position, while a plantar flexed in the second one.

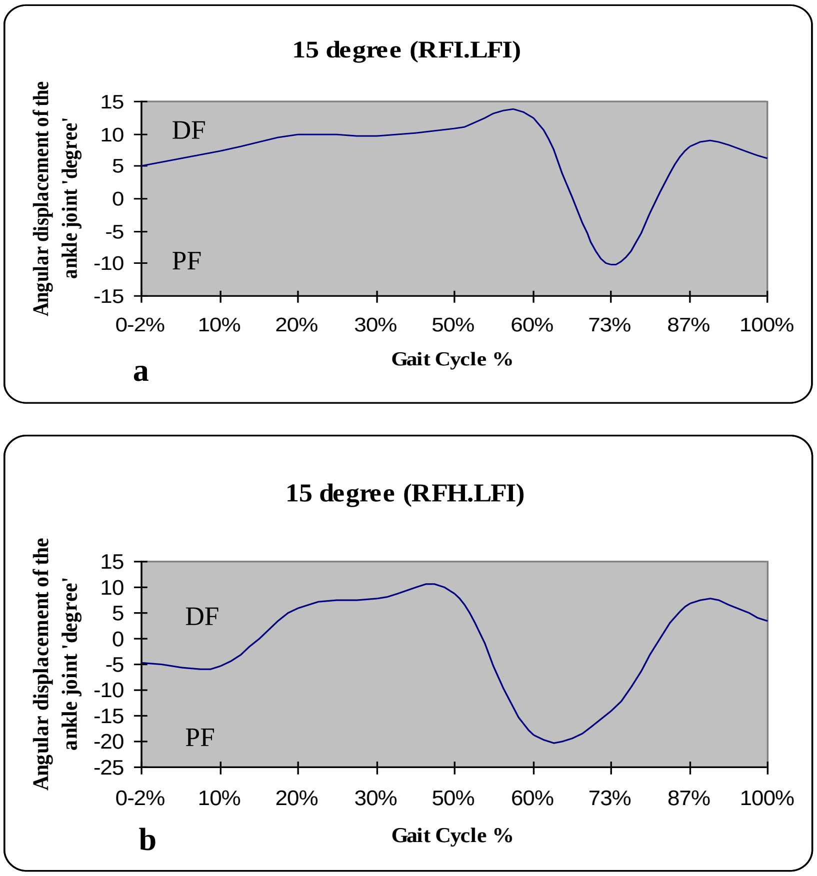


Fig. 59: Angular displacement of the ankle joint during walking up a ramp of 15º in the first (a) and second (b) positions.

The difference between the ROM of the ankle joint at the first position of walking up the three ramps was as follows

There is a gradual increase in the dorsiflexion angle by increasing the angle of walking ramps at the early stance phase. While at the late stance phase there is a delayed stance phase percentage which is 73% of the gait cycle (the normal occurred at 60% of the gait cycle). It was also observed that during the swing phase, there is a decrease in the percentage of the swing phase as it reached about 30% of the gait cycle (the normal swing phase represented about 40% of the gait cycle) by increasing the angle of walking ramps (fig. 60).

The difference between the ROM of the ankle joint at the second position of walking up the three ramps was as follows

The ankle joint assumed a planter flexed position at the early stance phase, then it moved gradually towards a dorsiflexed position at the mid stance phase while walking ramps in the second position. While at the late stance phase the planter flexion angle increased gradually reaching its peak 15° (normal planter flexion arc 20°- 30°) at about 63% of the gait cycle. It was also observed that there is a gradual increase in the dorsiflexion angle of the ankle joint in the mid swing phase by increasing the angle of the ramps (fig. 61).

Therefore, the most apparent change, occurring between the first and the second position in the angular displacement of the right ankle joint while walking up the three ramps was that there was a delayed stance phase percentage (73% of the gait cycle) in the first position compared to 63% of the stance phase in the second position.

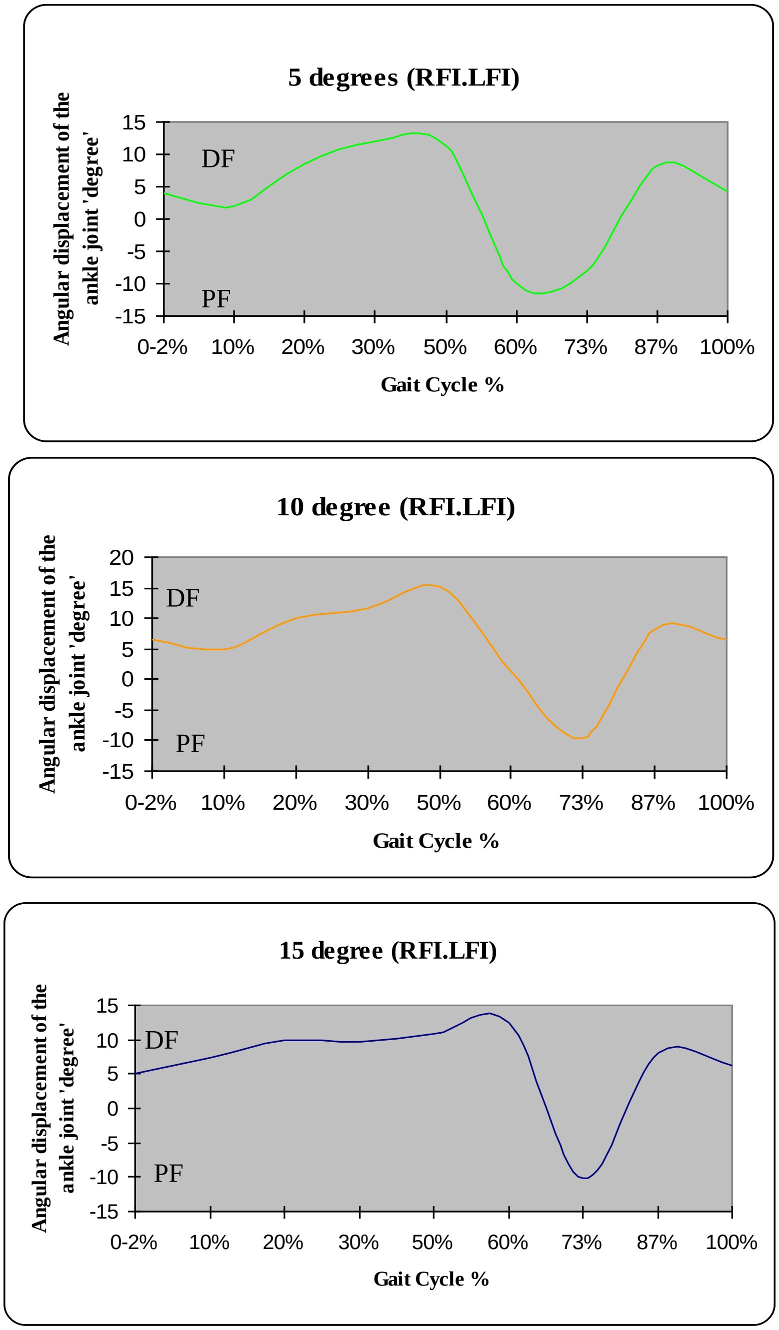


Fig. 60: Angular displacement of the ankle joint during walking up the three tested ramps in the first position.

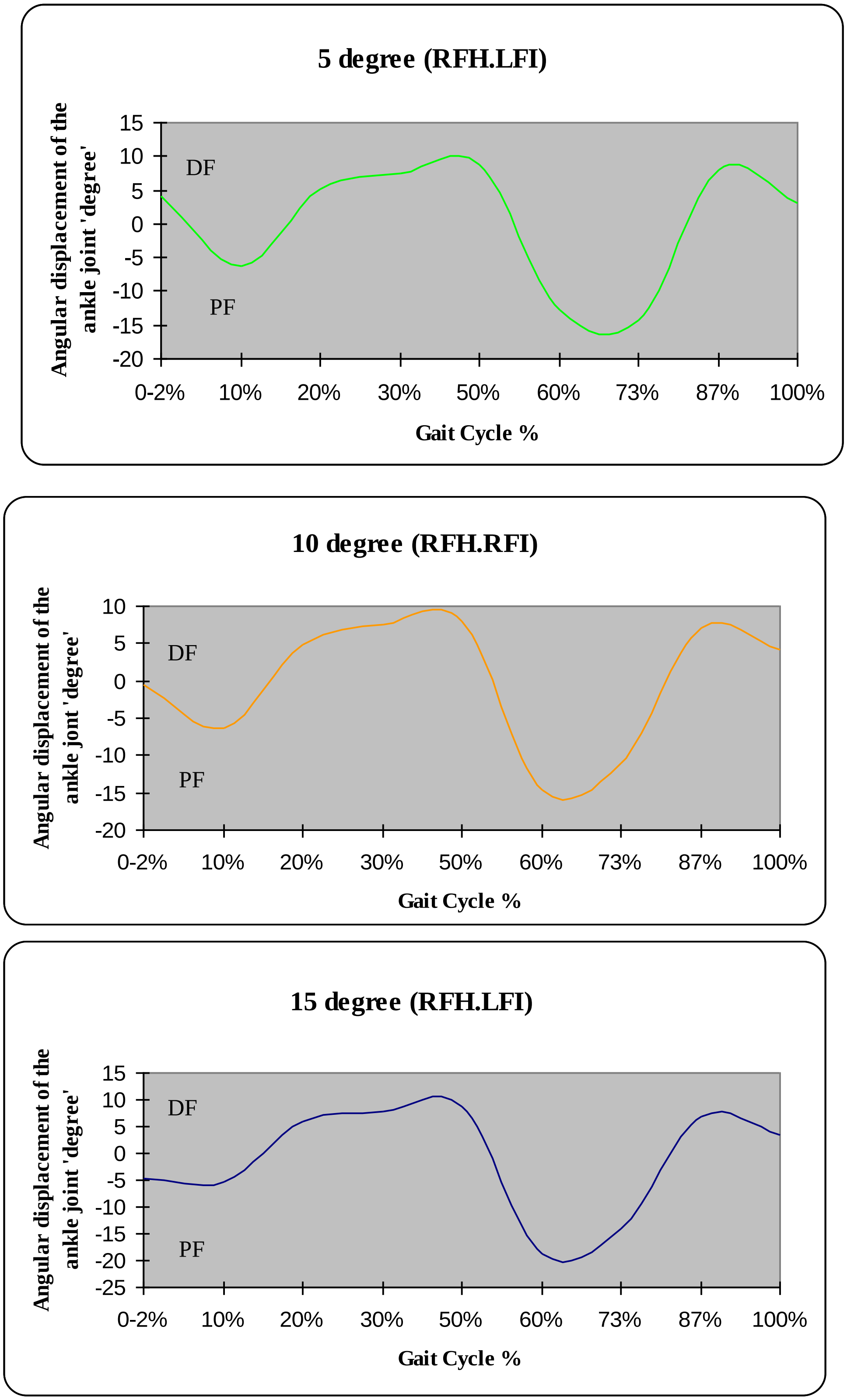


Fig. 61: Angular displacement of the ankle joint during walking up the three tested ramps in the second position.

Discussion

The purpose of this study was to investigate the effect of the three walking ramps (5º- 10º- 15º) on the magnitude of the vertical GRF and the ankle plantar flexion and dorsiflexion moments, each in two different positions during walking. In the first position, the right leg was placed on a ramp over the force platform and the left leg was placed on another ramp of the same degree placed at a distance to the left of the first one. This position is referred to as right foot inclination, left foot inclination (RFI, LFI). While in the second position, the right leg was placed on the force platform without a ramp and the left leg was placed on a ramp. In addition, the angular displacement of the ankle joint was recorded during walking up a ramp.

Analysis of the results demonstrated that there was no significant difference in the mean values of either the two peaks of the GRF for the three walking slopes in the first position. However, a significant difference was found in the mean values of F3 between ramp of 5º and 15º in the second position. A paired t-test also revealed that there was a significant difference in the mean values of F3 between the first and the second positions.

While, LSD multiple comparison post hoc test revealed that there was a significant difference in the mean values of the ankle DF moment between both ramps of 5º and 10º and ramps of 10º and 15º in the first position. However no significant difference was found in the mean values of the ankle PF and DF moments among the three walking slopes in the second position. A paired t-test also revealed that there was no significant difference in the mean values of the ankle PF&DF moments between the first and the second positions.

The first position

1- GRF

a- Effect of the three walking ramps on the two peaks of the GRF while walking

Statistical analysis showed that there was no significant difference in the mean values of the first and second peaks of the GRF among the three walking ramps, however, the 2nd peak had a higher value than the first one. This might be attributed to the fact that the value of the gravitational force varies slightly as the distance increases from the ground (Serway et al. 2004).

The above results are in accordance with the results obtained by Winter (1990). They studied the effect of ramps with different inclination angles of 0º and 10º on the magnitude of the vertical GRF and their results revealed that the 2nd peak of GRF had a higher value than the first one during walking up a ramp compared to level walking.

In the first peak of GRF, the right foot was supported on the ramp and the ramp is receiving the body weight while the left lower limb no longer contacts the ramp. So that the insignificant obtained in the first peak of GRF may be attributed to the fact that the initial double limb stance for both lower limb are the same in the three tested ramps. In this case the change in the ramp itself from 5° to 10° or 15° did not affect the value of the GRF first peak because the total surface area of the foot (foot flat sub phase) no longer happens. That means, in the three ramps the only region that contacted the ramp (5°, 10°, 15°) in the first position was the heel, so that the reaction from the ramp surface would be the same for all inclinations. While the insignificant difference in the second peak among 5°, 10°, 15° ramps in the first position may be due to the fact that both feet are working at the same level of inclination and no over activity is required to accommodate the difference between the right and the left foot.

The non significant difference in the mean values of the first and second peaks of the GRF among the three walking ramps in this study is supported by Findey (1970) and Haruhiko and Tokuhiro (1990). They conducted their experiments during walking up and down ramps of 1º up to 4º and found that there was no significant difference between the gait parameters of those walking up the ramp compared with those walking down it. Their findings also revealed during walking up a ramp that there was no significant difference in the mean values of the vertical GRF among the walking ramps.

The above results are further supported by Andrea et al. (2005). They studied the gait pattern of human during walking up & down a ramp of 0º, 15º and 39º and observed the variation in the magnitude of the vertical GRF. Their results revealed that there was no significant difference in the mean values of the first peak of the GRF however the second one increased significantly at 15º but not at 39º walking grade compared to 0º.

Although changing speed of walking alter the magnitude of GRF during walking on a level surface (Perry 1992). It was reported by Robert et al. (1998) that the ground reaction force during moderate speed running at 0º, 6º, and 12º inclines did not show significant change in its magnitude with incline.

However the results of this study were opposed with those obtained by Grampp et al. (2000). They examined the plantar loading changes during walking up and down on a treadmill of 0º, 8.5º and 15º inclines for 20 subjects using the pedar in shoe pressure measurement system. They measured the peak force (PF) in the heel, the five metatarsals and the hallux regions of the foot for each subject while walking. They found that during walking up a treadmill there was an increase in the PF over the first metatarsal and the hallux regions with an increase in the treadmill inclination. While they reported that during walking down it the PF in the heel regions were found to increase at 15º compared to level walking.

2- Moment

a- Effect of the three walking ramps on the right ankle PF\DF moments while walking

Statistical analysis demonstrated that there was no significant difference in the mean values of ankle PF moment among the three walking ramps. While, a significant difference was found in the mean value of ankle DF moment between ramp of 5º and ramp of 10 º and between ramp of 10º and ramp of 15º reaching its highest value at ramp 10º.

The significance found in the mean values of ankle DF moment between ramp of 10º and ramp of 15º may be attributed to the increased length of the dosiflexor at ramp of 10º (resulting from the increase in the plantar flexion angle of the ankle joint in the first half of the stance phase). According to the length tension relationship the increase in the muscle length leads to an increase in the tension generated by the dorsiflexors. (Frankel and Nordin 2001).

While the significance found in the mean values of ankle DF moment between ramp of 5º and ramp of 10º may be due to the increase in the stance period at which the foot remain in contact with the ramp up to 73% of the gait cycle during walking up a ramp of 10º compared to 63% of the gait cycle during walking up a ramp of 5º. Large portion of this percentage (73%) is occupied by ankle dorsiflexed position (nearly 60%) and the rest of this percentage (nearly 13%) is occupied by a planter flexion of the ankle joint (referred to figure 60).

As, the ankle joint is kept in a dorsiflexed position this moves the GRF vector posterior to the ankle joint which creates a planter flexion moment. This planter flexion moment is compensated by activity from dorsiflexors to maintain balance in this position (fig. 62). This explain why the dorsiflexion moment was reported to be higher in 10º walking ramp more than 5º. As, it was reported by Spoor et al. (1990) and Maganaris et al. (2003) that the muscle-tendon moment arm length, i.e. the perpendicular distance from the muscle-tendon action line to the rotation centre of the joint that the muscle-tendon spans, is responsible for transforming muscle force and linear displacement to joint moment and rotation. Their study was on in vivo measurements of human muscle-tendon moment arms at rest and during isometric maximal voluntary contraction (MVC). The ankle joint was set either at -15°, 0°, 15°, and 30° (0°: anatomical position, positive values for plantar flexion). The results obtained by actual measurements on 2-D magnetic resonance images indicate that the moment arm lengths of the tibialis anterior tendons increase during MVC compared with rest by between 22% and 44% due to (1) ankle joint displacement, (2) muscle thickening and (3) stretching of collagenous structures mediating the action of tendon. Therefore, as the moment arm lengths of the tibialis anterior tendons increase during MVC compared with rest in the previous study, transition of the ankle joint from a dorsiflexed position at 50% of the gait cycle to a planter flexed position at 73% of the gait cycle during walking up a ramp 10° in this study may be attributed to an increase of the dorsiflexor ́ s moment arm that contribute significantly to increase the dorsiflexion moment.

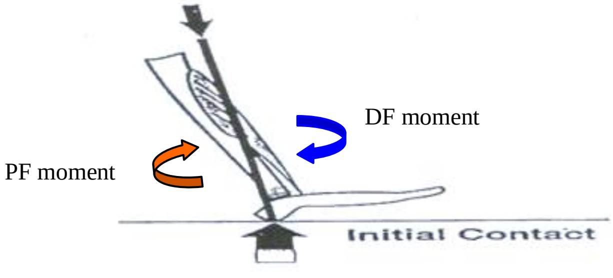


Fig. 62: The GRF vector posterior to the ankle joint creates a PF moment (black arrow) compensated by a DF moment (blue arrow). (Adapted from Perry 1992).

The above results are supported by Takuhiro et al. (1985) that there was a continuous activity in the tibialis anterior muscle in the latter part of the midstance and push off phases while walking up ramps of 3º, 6º, 9º and 12º. The tibialis anterior plays two important roles stabilizing the ankle joint as the body rises against the effect of the gravity and clearing the toe against the terrain. Moreover, the tibialis anterior was found to inhibit excessive planter flexion of the ankle joint at push off phase. This is due to its eccentric contraction which causes significant difference in DF moment during walking.

The above results are further supported by Red fern et al. (2001). They found that the moment generated at the ankle joint during walking down a ramp showed a significant difference in the mean values of the ankle PF & DF moments between the walking ramp of 0º, 5º, 10º, 15º, and 20º. They observed that the highest DF moment occurred at a ramp of 20º and the least value occurred at ramp 0º while the highest PF moment occurred at ramp 0º and the least value occurred at ramp 20º. These findings indicated that the variation of the angular displacement of the ankle joint during walking up a ramp compared to its walking down had a vital role in the generated ankle moment. As it was reported by Winter (1991) that the ankle joint assumed a greater degree of ankle plantar flexion and dorsiflexion angles during walking down a ramp of 0º, 5º and 10º that contribute significantly to the increase in the generated moment. They found that at heel contact the ankle was in a slight dorsiflexion but rapidly moved toward plantar flexion as the foot rotates down into a floor. Then the ankle was gradually moved into dorsiflexion at pre swing phase. While, it was reported by Andrea et al. (2005) that during walking up a ramp of 0º, 15º&39º the peak ankle plantar flexion moment increased uniformly compared to walking at 0º. They reported that the ankle joint was more dorsiflexed as the walking grade increased.

Different results were obtained by Thomas et al. (2005). They measured moments at the ankle, knee and hip joints during moderate speed running at 0 º, 6 º and 12 º inclines. Their results revealed that the ankle function during incline running was similar to that of the level running and there was no significant difference between the ankle moments while running at these ramps. They attributed that to an increase in the work produced at the hip joint that represents 75% of the net work performed by the knee and ankle joints. This increase in the work produced at the hip joint is due to the increase in the moment arm of the GRF which was oriented further anterior to the hip joint, thus, increasing the moment arm, the associated moments and work output during uphill running.

3- Relationship between the GRF and the ankle moments while walking up a ramp

Analysis of the correlation coefficient in the mean value of the two peaks of GRF and ankle moments between the walking ramps showed no significant correlation in the mean value of F1 and DF moment between the walking slopes. While a significant positive correlation was found in the mean value of F3 and PF moment at ramp of 5º. Also, there was a significant correlation in the mean value of F3 and PF moment at ramp of 10º. This indicates that an increase in the degree of the supporting surfaces the PF moment and the magnitude of the F3 also increase.

The significant correlation in the mean value of the ankle PF moment and F3 was in accordance with the findings of Richard and Kotarso (2005). They reported that the plantar flexors are the primary contributors to the observed GRF during the propulsive phase. Thus, if the forces produced by the plantar flexors decreased a corresponding decrease in the GRF will be expected during the propulsive phase.

Decreasing the walking speed with increasing the angle of inclination of the supporting surfaces altered the magnitude of the GRF and affects the plantar flexor force production (Whitt 1999). As it was reported by Thomas et al. (2005), the mean PF moment produced at the ankle joint during uphill running at 6º, 9º, and 12º inclines was found to have a higher value than that walking at a normal speed. These variations at the ankle PF moment were associated with an increase in the magnitude of the vertical GRF. This explains the correlation between the mean values of PF moment and F3 during walking up different ramps and at different speeds.

The previous results are further supported by Andrea et al. (2005). They found that the plantar flexion moment of the ankle joint was significantly increased while walking a ramp of 15º and 39º and this increase was associated with an increase in the second peak of the GRF.

The second position

1- GRF

a- Effect of the three walking ramps on the two peaks of GRF while walking

Statistical analysis of the results demonstrated that the highest value of F1 occurred at ramp of 10º with a mean value of 110.56 % BW and the least value occurred at ramp of 15º with a mean value of 107.37 % BW. While highest value of the F3 occurred at ramp of 15º with a mean value of 122.21 % BW and the least value occurred at ramp of 5º with a mean value of 116.7 % BW.

This variation in the mean value of F1 was not statistically significant among the three tested walking ramps. However, there was a significant difference in the mean value of F3 between ramps of 5º and 15º.

As mentioned before, the non significance difference obtained in the first peak of GRF may be attributed to the fact that the initial double limb stance for both lower limbs is the same in the three tested ramps. As it was observed that the right foot in the second position was supported on the ground and the ground is receiving the body weight while the left lower limb no longer contacts the ramp, therefore, change in the ramp itself did not affect the value of the first peak of the GRF because the total surface area of the foot (foot flat sub phase) no longer happens. So that the reaction from the ground surface in the second position would be the same for all inclinations.

While the significant difference in the mean value of F3 among ramps of 5º and 15º may be attributed to the work of the plantar flexor which has to produce much force as the angle of inclination of the supporting surface increases. This is to enable the body to be elevated against the ramp. The position of the right foot in 5° resembles the normal walking pattern while in 15° ramp, the right foot was on the ground for contact and the left foot advances to the 15° ramp so the right foot should elevate the body upward to accommodate for the elevated left foot. This also explains why the 2nd peak of GRF increases on 15° ramp compared to that of 5°.

The above results are in accordance with the results obtained by Stacoff and Diezi (2005) who made their study on three different stair inclinations (24º-30º&42º) and three different age groups (young , middle and old age) and compared data of vertical (GRF) parameters for twenty healthy subjects during level walking, stair ascent and descent. Their results showed that during level walking the vertical GRF curves were very regular and repetitive, the trail-to-trial variability and left-right asymmetry of defined test parameters being around 2-5% and 3-5%. During stair ascent the vertical GRF force pattern was found to change slightly compared to level gait, but considerably compared to stair descent. While on the steep stair the average vertical load increased up to 1.6 BW, and variability (5-10%) and asymmetry (5-15%) were increased significantly. They also reported that the young age group walked faster due to an increase of their walking speed and produced larger vertical GRF during level walking and on stair ascent than the middle and old age group.

Thus, an increase in the mass of the materials of the ramps causes an increase in the value of the vertical GRF during walking. This was also reported by Kaufiman (2001) who stated that the vertical ground reaction force contributed significantly to joint reaction force (JRF). Also, the material used to design insole inside the shoes to correct the deformities, must be made of certain materials with a little mass to reduce the value of the (GRF) and consequently the value of the (JRF) during walking especially in elderly subjects who suffer from osteoporosis and arthritic changes. Therefore, it was reported by Vernon and Grace (2004) that the magnitude of the impact vertical GRF increased significantly while wearing the Masai Barefoot Technology (MBT) shoe due to its high mass. This shoe has a rounded sole in the anterior-posterior direction providing uneven surface during walking. It was used to reduce the cyclic loading of the structures that comprise lower limb joints (fig. 63).

Fig. 63: The Masai Barefoot Technology (MBT) shoe. (Adapted from Vernon and Grace 2004).

2- Moment

a- Effect of the three walking ramps on the right ankle PF/DF moments while walking

Statistical analysis of the results revealed that the mean value of PF moment was 1.62 Nm/Kg at ramp of 10º and 1.51 Nm/Kg at ramp of 5º. While, the mean value of DF moment was found to be 0.16 Nm/Kg at ramp of 5º and 0.17 Nm/Kg at ramp of 15º.

The results of the study also revealed that the mean value of PF moment had a higher value than that of the DF moment while walking up the three tested walking ramps. However, no significant difference was found in the mean values of PF and DF moments among the walking slopes.

An increase in the mean value of PF moment may be attributed to the large cross sectional area of the plantar flexor muscles which have a direct role for increasing the PF moment during walking (Neumann 2002). Therefore, it was reported by Tetsuro et al. (2005) that the ankle joint moment generated inside gastrocenemius muscle during walking is greater 5.4 Nm\K than that generated during standing 2.3 Nm\Kg. They postulated an increase of the ankle plantar flexion moment during walking to the variation of the muscle fascicle length in the medial gastrocenemius muscle which was shortened by 2.9 mm during standing causes a decrease in the passive joint moment from 19.9% to 17.4%. In addition, it was reported by Oatis (2004) that an increase in the generated PF moment plays a vital role to lift the body against the ground which in turn increases the reaction force at push off phase.

The above results are in accordance with the results obtained by Hamill and Knutzen (2003). They reported that moving from a level surface to an inclined one causes increase in the knee flexion angle, this to locate the foot more medially. As shown in figure (64) the increase in the knee flexion angle will move the line of gravity more anterior to the axis of the ankle joint and produce dorsiflexion moment. This had to be compensated by a plantar flexion moment (PF) to rotate the leg posterior and bring the knee towards extension which causes an increase in the ankle PF moment. Therefore, it was reported by Andrea et al. (2005) that the knee extension moment KM2 in figure (65) increased significantly to compensate the flexion moment caused by the GRF vector during walking at the steepest grade of 15º& 39º. It was also reported by Oatis (2004) that the plantar flexors provide the necessary force to lift the body weight from the floor and enable the subject to make a new step.

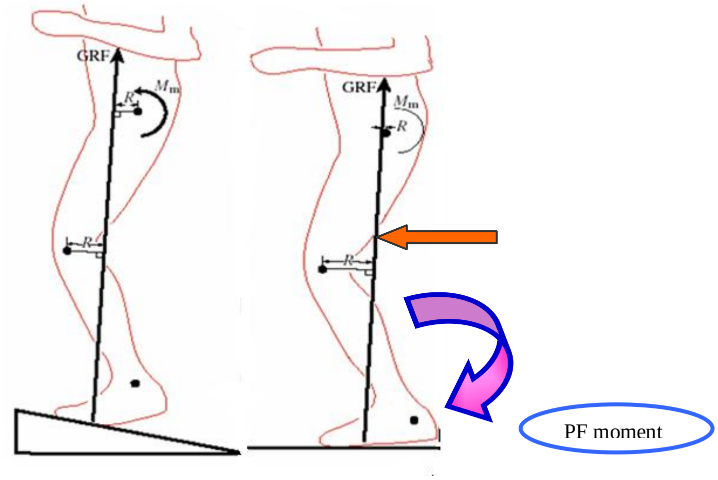


Fig. 64: Diagrams of force and limb position during walking up a ramp in the 2nd position. The black arrow represents the GRF and its moment arm R. (Adapted from Thomas et al. 2005).

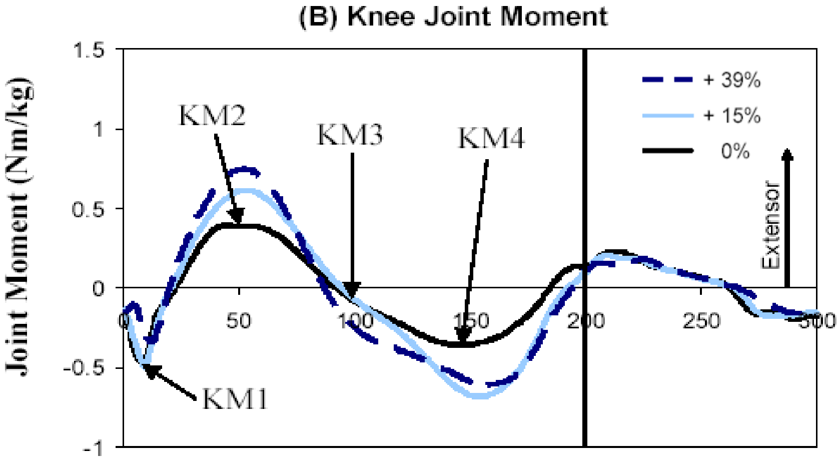


Fig. 65: The significant increase in the knee extensor moment during walking a ramp. (Adapted from Andrea et al. 2005).

3- Relationship between the GRF and the ankle moments while walking up a ramp

Using a correlation tests, the relationship between the first peak of the GRF (F1) & the DF moment as well as the second peak of the GRF (F3) & the PF moment were tested. Results revealed that there was no significant correlation ($P > 0.05$) between both of F1 and DF moment at a ramp of 5º ($r = -0.2$), ramp of 10º ($r = -0.2$) and at a ramp of 15º($r = -0.2$).

Meanwhile, the relationship between the mean values of the second peak of the GRF (F3) and the ankle plantarflexion moment (PF) was also tested using a correlation test. Results revealed that there was a significant correlation ($P < 0.05$) between both of F3 and PF moment at a ramp of 5º ($r = 0.4$) and at a ramp of 10º ($r = 0.5$). However, there was no significant correlation at a ramp of 15º ($r = 0.3$). This indicates that by increasing the magnitude of the PF moment, the mean value of F3 increases. This is true for walking up ramps of 5 and 10 degree.

The significant positive correlation between the mean value of F3 and the PF moment was in accordance with the results reported by Anderson and Lagerof (2003) and Neptune and Sasaki (2004). The results of their study revealed that an increase in the plantar flexors′ force production was accompanied by an increase in the magnitude of the GRF at the push off phase during walking.

The above results are also in accordance with the results obtained by Riener et al. (2002). They studied the biomechanics and motor coordination in the human during stair climbing at different inclinations (24º, 30º and 42º). They reported that the generated ankle moments were relatively low but directly dependent on the degree of an inclined surface when compared to a level walking. They postulated their findings to varying the amount of potential energy that has to be produced during ascent or absorbed during descent.

The results of the present study are further supported by Hasio and Nashner (1999) and Oatis (2004). They found that the DF moment caused by the anterior orientation of the GRF caused an increase in the PF moment around the ankle joint which in turn increased the magnitude of the GRF at the push off phase. This increase in the PF moment was needed to clear the toes off the walking slopes. As, it was reported by Mcfayden (1997) that the foot is needed to be lifted higher during stair walking compared to level walking to overcome the displacement of the body's centre of gravity C.O.G.

- **Comparison between the first and second positions of walking ramps with regard to the mean value of the two peaks of GRF and ankle moments**

1- GRF

Testing the difference between the first and second positions with regard to the mean values of the two peaks of the GRF showed that there was a significant difference in the mean values of F1 and F3 during walking up a ramp of 5º. That means F1 and F3 assumed together greater significant values between the first and the second position during walking up only a ramp of 5º. Also there was a very high significant difference in the mean value of F3 between the first and the second positions during walking up a ramp of 10º and 15º. That means the magnitude of F3 assumed only a greater significant value during walking up a ramp of 10º and 15º in the second position if it is compared to the first one.

According to Newton's law of gravitation: all bodies attract one another with a force proportional to the square of the distance between them. That is, $F \propto \frac{m1m2}{r2}$ where m1 and m2 are the masses of the two bodies, r is the distance between them and F is the amount of the gravitational attraction between an object and earth.

Therefore, the reaction force between the subject's leg and the earth surface in the second position in which the foot was in direct contact with the ground increases to enable the subject to accelerate the body up and forward during slope walking. As it was reported by Tetsuro et al. (2005) that elevation of the body during walking up a ramp is the primary contributors to the observed increase in the GRF value during the propulsive phase.

Moreover, it was reported by Serway et al. (2004) that walking on an inclined surface reduces the subject's acceleration which in turn reduced the magnitude of the vertical GRF in the first position as there is a direct relationship between the acceleration and the values of the reactive forces during walking ($a= \frac{F}{mass}$).

2- Ankle moment

Using paired t-test to compare between the two tested positions for the mean value of each of the ankle planterflexion and dorsiflexion moments, results revealed that there was no significant difference (P > 0.05) between both positions for each of the plantarflexion and dorsiflexion moments.

The absence of the significant difference in the mean value of the ankle planterflexion and dorsiflexion moments may be attributed to the slight variation occurred between the two tested positions in the angular displacement of the ankle joint while walking up the three ramps. According to torque angle relationship, there is a direct relation between the angular displacement of the ankle joint and the moment generated around it (Enoka 2002).

As, the generated moment around the ankle joint is affected by the orientation of the GRF vector while walking, the magnitude of this moment was directly affected by the angular displacement of the ankle joint (Perry 1992). Therefore, it was reported by Thomas et al. (2005) that a decrease in total joint excursion during uphill running of 0º, 6º and 12º associated with an increase in the ankle joint moment (fig. 66).

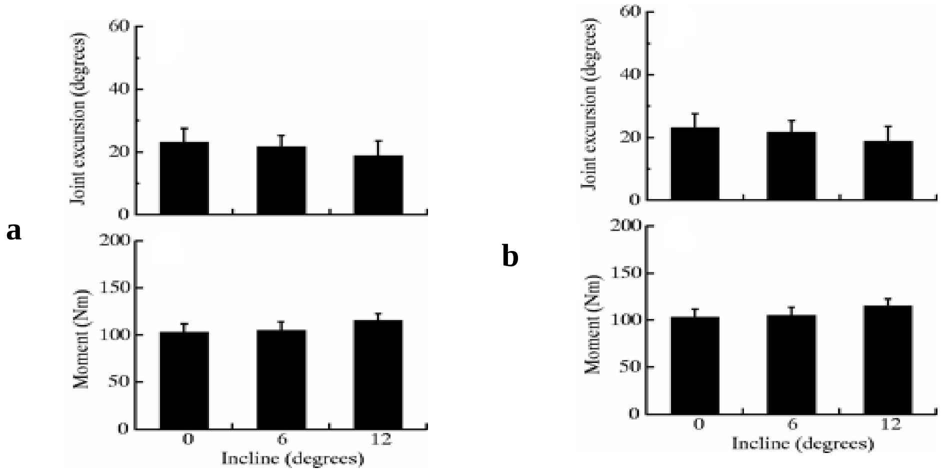


Fig. 66: The variation between the ankle joint moment (b) and its angular displacement (a) while up hill running of 0º, 6º &12º. (Adapted from Thomas et al. 2005).

Kinematic analysis of gait:

Analysis of the results revealed that using different walking ramps produced different angular displacement of the ankle joint related to the degree of slope inclination in the first and second positions. The observed difference between the first and the second positions while walking up a ramp of 5º was that the ankle assumed a dorsiflexed position as the heel contacts the ground early in the stance phase at the first position while it moved toward plantar flexion in the second one.

The differences observed between the first and the second positions during walking up a ramp of 10º were that the ankle joint was dorsiflexed at the beginning of the stance phase in the first position whereas a plantar flexed ankle was observed in the second one. It was also observed that the ankle assumed a planter flexed position about 10° up to 73% of the gait cycle in the first position while there was a gradual increase of the ankle planter flexion that reached 15° at 63% of the gait cycle in the second one.

During walking up a ramp of 15º the angular displacement of the ankle joint revealed that the heel contact the ground with the ankle dorsiflexed at the early stance in the first position while a plantar flexed ankle was observed in the second one. Moreover, it was observed that in late the stance phase the ankle was dorsiflexed in the first position while a plantar flexed ankle occurred in the second one. It was also observed that the angular displacement of the ankle joint during walking up the three ramps in the swing phase was nearly the same in the first and the second positions.

The previous results are supported by the findings of Andrea et al. (2005). They found that the ankle joint was progressively more dorsiflexed at heel strike (AA1) in figure (67) as the walking grade increased. They also found that during upslope walking at 15º& 39º the ankle joint was dorsiflexed until late stance. While the upslope and level walking ankle angles were similar only in late stance and early swing (AA3) in figure (67).

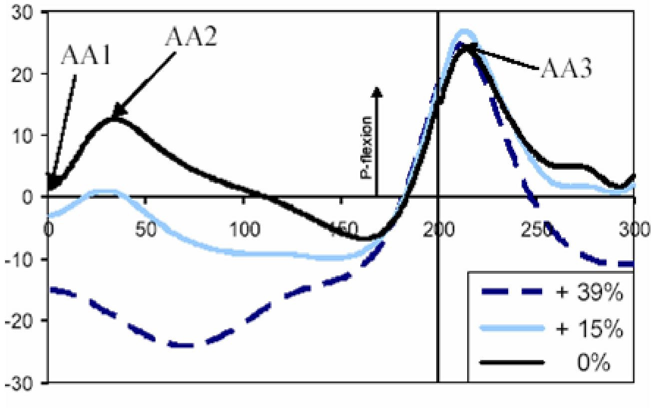


Fig. 67: Angular displacement of the ankle joint during walking up a ramp. (Adapted from Andrea et al. 2005).

The above results are in accordance with the results obtained by Leroux et al. (2002). They found that increasing the treadmill grade from 0° to 10° induced an increasing of the flexed posture of the ankle joint from early stance to mid swing phase.

It was also reported by Thomas et al. (2005) that the total angular excursion of the ankle joint during uphill running of 0º, 6º and 12º was very similar to that of level running and was independent on the degree of an inclined surface reaching about 30º dorsiflexion during the stance phase of the gait cycle. Moreover, it was reported by Mcfayden et al. (1997) the differences in anticipatory locomotor adjustments during walking over obstacles. They observed that the ankle was more dorsiflexed at the first part of the swing phase at it involved less plantar flexion angle at toe off as compared with the walking without an obstacles.

However, the results of this study were opposed with those obtained by Redfern et al. (2001). They studied the kinematics of inclined surfaces as walking down a ramp and reported that at heel contact, the ankle was in a slight dorsiflexion but rapidly reaches into a plantar flexed position as the foot rotates down into a floor. Then the ankle was gradually moved into dorsiflexion at preswing phase while it assumed a plantar flexion position in terminal swing phase.

Implementation:

The primary function of the ankle and foot is to absorb shock and import thrust to the body during walking. So, the foot must be pliable enough to absorb the impact of millions of contact throughout a life-time. The healthy foot satisfies the paradoxical requirements of both shock absorption and thrust through an interaction of interrelated joints and muscles. Through understanding the biomechanics of ankle/foot complex, an accurate description of the appropriate shoe modifications or orthoses could be done. This is done in an attempt to modify weight transfer patterns.

The findings of this study showed that there was a significant difference ($P < 0.05$) between both positions for F3 at each of a ramp of 5º, ramp of 10º and ramp of 15º. The value of F3 significantly increased in the second position when the foot was on a ground compared to its value in the first position when the foot was on a ramp. In the light of these findings, designing the anterior wedged insole with the suitable angle of inclination has important implications in prosthetics and assistive devices. It can be used inside the shoes of spastic patients figure (68) and drop foot patients figure (69) to support the anterior aspect of their foot and allow proper heel contact. In addition it may reduce the value of GRF and consequently the value of JRF during walking compared to their value without the angle of walking insole (fig. 70&71).

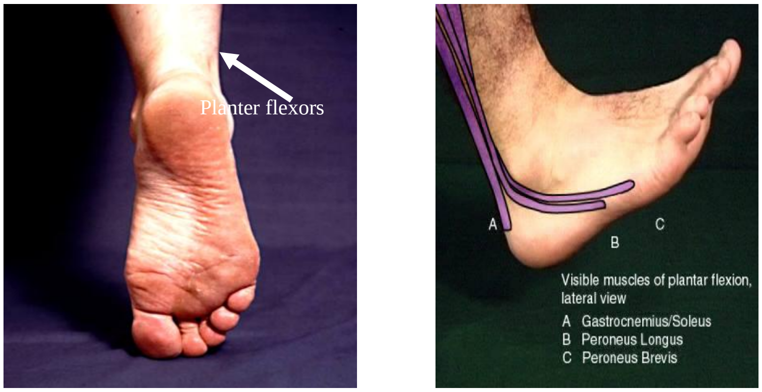


Fig. 68: In spastic foot, there is persistent ankle planter flexion due to spasticity of the planter flexors.

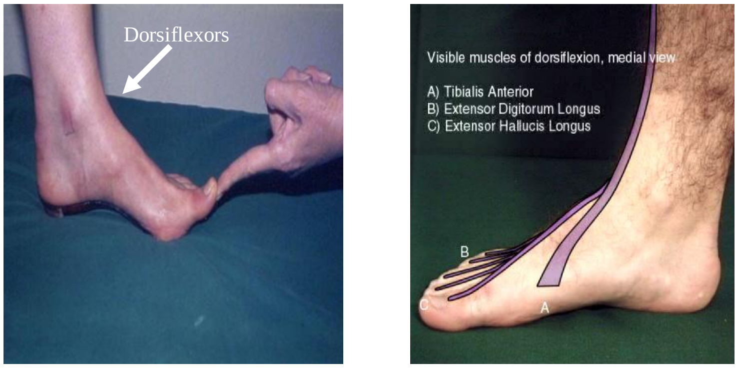


Fig. 69: In drop foot, there is low heel and fore foot contact occurs when the foot strikes the floor due to weakness of the dorsiflexors.

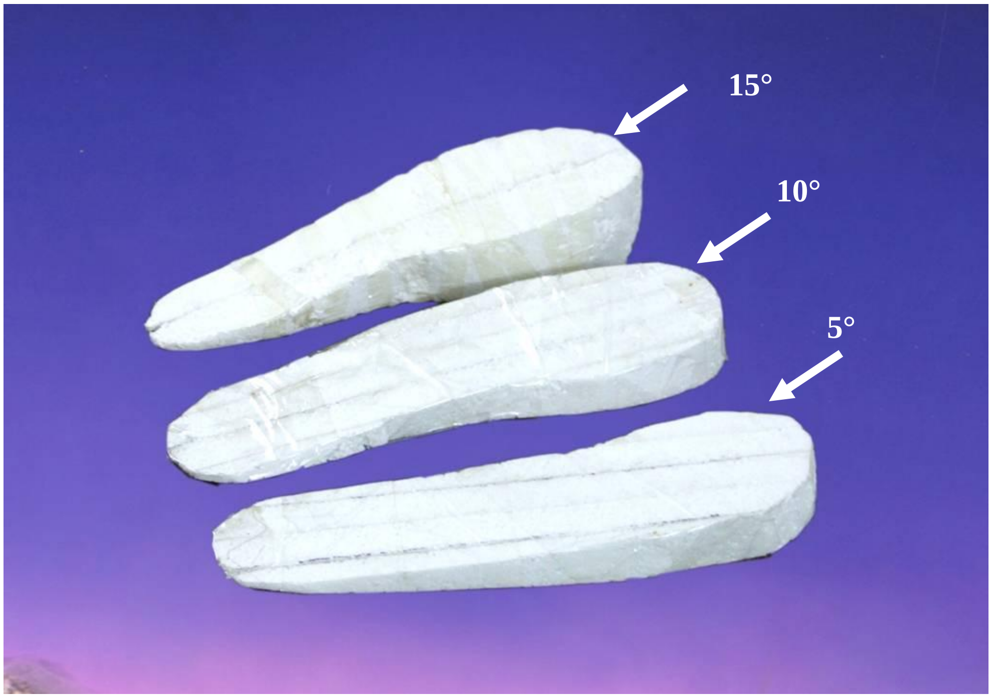


Fig. 70: The recommendede anterior wedged insoles to be used inside the shoes of spastic or drop foot patients. (Designed according the present study).

Fig. 71: The recommended anterior wedged insoles can be used inside the ankle foot orthosis (a) or in the medical shoes (b).

Different shoe modifications like the rocker sole figure (72 a) and the extra–depth shoe figure (72 b) were introduced by Seymour (2002). The Rocker sole is afirm material which has an anteriorly and posteriorly skived edge. The rocker sole project approximately 1/4 to 1/2 inch below the level of sole and extend proximally to the metatarsal heads. It allows wider distribution of weight. Therefore, body weight is shifted more from the metatarsal head to the metatarsal shaft. It is often used for insensitive foot and may be helpful for those prone to skin breakdown over the metatarsal heads. However, the Extra–depth shoe provides the foot with additional space to accommodate any orthoses that are necessary.

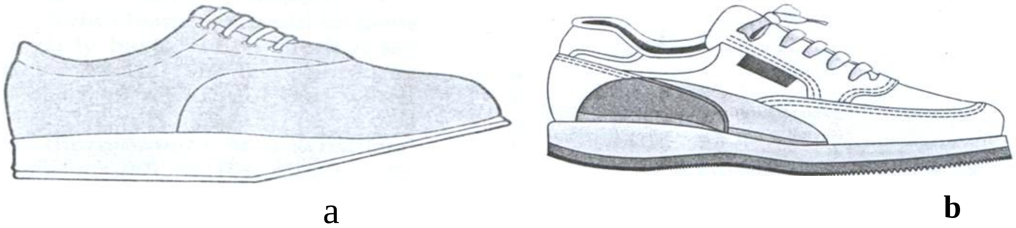


Fig 72: Different types of shoe modification, a- Rocker sole and b- Extra-depth shoe**.** (Adapted from Seymour 2002).

A special type of ankle–foot orthoses (AFO) was introduced by Ranawat and Positano (1999) and Ferris et al. (2005). This type of orthosis can be used during the chronic phases of posterior tibial tendenitis while the foot is still flexible. The purpose of this orthosis is to support the flattened arch during walking (fig. 73) Posterior night splint has been widely used for the treatment of the achillis tendenitis. The splint is an ankle–foot orthosis positioned in about 5̊ of dorsiflexion worn only at night. The purpose of this splint is to prevent contractures in individuals with neuromuscular disease and in patients confined to bed.

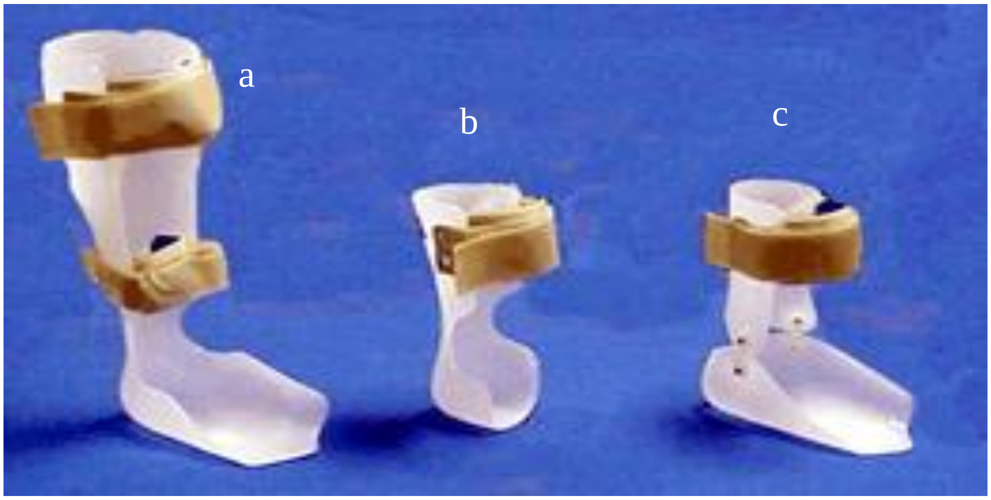


Fig. 73: Three different type custommade foot orthoses: a) a rigid ankle foot orthosis (AFO), b) a rigid hindfoot orthosis (HFO-R), and c) an articulated (HFO-A) hindfoot orthoses. (Adapted from Ferris et al. 2005).

It was also observed that there was a delayed stance period percentage (73% of the gait cycle) in the first position (referred to figure 60). This may be attributed to tendency of the subject to maintain the dynamic stability during walking up a ramp. Therefore, the non affected limb of the hemiplegic patients remain in contact with the ground for a longer period of the stance time to prevent any disturbance of his stability during walking as there is persistent ankle plantar flexion and inability to rise on the metatarsal heads. Also in drop foot patients, there is low heel and forefoot contact occurs when the foot strikes the floor with the ankle in 15º plantar flexion and the knee fully extended and entry into loading response phase would be sudden (Perry 1992). So during walking up a ramp the hemiplegic and drop foot patients were advised to take the first step with the non affected side to achieve a greater percentage of the stance time and consequently a greater stability during walking.

Summary and conclusion

This study was conducted in the gait analysis laboratory, Faculty of Physical Therapy, Cairo University. Thirty male subjects participated in the study. The purpose of the study was to investigate the effect walking up ramps of three different angles (5º- 10º- 15º), each tested at two different positions on the magnitude of the vertical ground reaction force (GRF), right ankle plantar flexion (PF)/dorsiflexion (DF) moments and the angular displacement of the right ankle joint. The two tested positions used in this study were: in the first position, the right leg was placed on a ramp over the force platform and the left leg was placed on another ramp of the same degree placed at a distance to the left of the first one. While in the second position, the right leg was placed on the force platform without a ramp and the left leg was placed on a ramp.

The test was conducted using Motion Capture Unit (MCU) which consists of six infrared high speed Pro Reflex cameras and the AMIT force plate unit (Advanced Mechanical Technology Inc., USA). It measured the vertical GRF and the internal moments generated by the ankle muscles in addition to the range of motion of the ankle joint while walking.

The subjects were allowed to stand in front of the walkway and the reflective markers were positioned on the twenty specified bony landmarkes of the body. They were instructed to perform two trials while walking up the three slopes in the first and the second positions without targeting on the force platform.

Statistical analysis using Repeated Measures ANOVA revealed that there was no significant difference among the three ramps ($P > 0.05$) for each of the two peaks of the GRF. This is while walking up any of these three tested ramps in the first position. However, it was found that there was a significant difference in the mean values of F3 between slope 5° and 15° ($P < 0.05$) in the second position. In addition, paired t-test showed that there was a significant difference between the first and the second position with regard to the mean values of F3 at each of the three walking ramps ($P < 0.05$).

The findings also showed that there was no significant effect among the three ramps for the ankle PF moment while walking up in the first position ($P > 0.05$). However, a significant difference among the three tested ramps for the ankle DF moments ($P < 0.05$) with a ramp of 10º achieving the highest recorded moment. While in the second position, it was revealed that there was no significant difference among the three ramps on the ankle PF and DF moments ($P > 0.05$). In addition, paired t-test showed that there was no significant difference ($P > 0.05$) between the first and the second positions with regard to the mean values of the ankle PF and DF moments during walking.

The results of this study concluded that changing the angular displacement of the ankle joint while walking up a ramp in the first position was associated with a change in the internal DF moment. The highest value of DF moment was recorded while walking up a ramp of 10º. Therefore, this study can help ergonomists to accurately design walking surfaces of an appropriate ramp that will achieve the least ankle moments while walking.

Conclusion

It can be concluded that the optimal ramp that is associated with the least DF moment while walking was 5º. Also, it was concluded that an increase of the materials ramp leads to an increase in the value of the vertical GRF during walking. Thus, it is preferable to design ramps with little material.

Recommendation

Based on the results of this study it is recommended to apply the same study:

1- On a bigger sample size.

2- On the left ankle joint.

3- On patients with common pathological conditions affecting the joints and muscles of the ankle and foot e.g. drop foot and spastic foot.

4- On female subjects to determine if there is any effect of sex on the peak values of the GRF and on the ankle PD/DF moments.

5- On different age groups to determine the effect of age on the peak values of the GRF and on the ankle PD/DF moments.

6- Using a big variation of the walking ramps.

7- Using wedged insoles which have the same angles of the three walking ramps to determine their effect on the ankle moments and GRF values during walking.

8- Using electromyography in conjunction with the 3-D Motion Analysis System to determine the activity of the dorsiflexors and plantar flexors during ramp walking.

9- With examining the ankle joint at different planes of motion.

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