METHODS AND PROCEDURE VALIDATION OF TRANSVERSE PLANE SLOPED SURFACE WALKING GAIT: A KINEMATIC AND KINETIC ANALYSIS

Josh Quincy, University of Utah
Andrew S. Merryweather, University of Utah
Donald S. Bloswick, University of Utah

Josh.Quincy@gmail.com

ABSTRACT

Little research has been done on sloped surface gait dynamics. This paper documents a pilot study conducted to validate proposed methods for data collection of sloped gait. Trials were performed on an adjustable 9.14 meter track. The track was used at the horizontal and at a slope of 13°. Optical markers were placed on the subject to record lower limb position to model the joint displacement. A force plate located in the track recorded ground reaction forces. Through reverse dynamics all joint forces and moments were calculated. Joint angles, forces and moments recorded at the level and sloped track conditions were compared for any significant differences. Significant differences were found in the angles, forces and moments of both the knee and ankle.

INTRODUCTION

In 2004 walking injuries accounted for 14.9% of all railroad worker injuries resulting in 19.3% of days absent (Federal Railroad Association, 2005). Some railroad workers spend a significant portion of their time walking along track lines on a sloped surface of ballast (rock). The slopes of the walking surfaces vary, reaching slopes of 10°. It is yet to be determined if the sloped surfaces contribute to injury.

According to the NSC Injury Facts Report, the average incurred cost for knee injury claims was $17,000 in 2002. Potential risk factors associated with musculoskeletal injuries of the lower extremity include obesity, rear foot motion, and repetitive, high dynamic knee joint loads (Hunt, 2001).

The effect of walking on sloped surfaces in lower extremity kinematics has not been thoroughly investigated to describe the changes in biomechanical forces at lower extremity joints. There is limited published data (Andres, 2005, Lay, 2005, Lay, 2006, McIntosh, 2005, Schwameder, 2005) describing gait on sloped surfaces. McIntosh found differences in the mechanisms by which the body enables walking up and downhill, showing the need for added muscle or prostheses strength. Lay (2005) investigated the neural control while walking up and downhill. He found that there may be different control systems for level, uphill and downhill walking. Andres (2005) examined slopes in the transverse plane. He investigated rear foot motion while walking on different ballast. No significant motion was found for walking on sloped surfaces while on a surface of either concrete or a walking (small gravel) ballast. On mainline (large gravel) ballast rearfoot motion was detected.

To better understand gait on sloped surfaces, a study, which quantitatively describes the effects of uneven walking surfaces in the transverse plane on walking gait, will be performed. Measurements will be taken of participants while traversing simulated walking surface conditions in a laboratory controlled environment to describe movement. A biomechanical model will be generated using the data collected from study trials to identify alterations to normal, flat surface walking gait patterns.

This study is unique in that no prior research has recorded kinetics while walking on a surface sloped in the transverse plane. Before the study can be performed, pilot studies need to be done. This is to ensure the validity of the proposed methods and equipment to be used. This paper is on the research which has been done to test and verify the accuracy of recorded results for the proposed experiment. Data was recorded for level walking to compare against current literature and the data from the sloped surfaces. Data will be considered accurate if the level gait analysis matches data reported in literature.

METHODS

Subject Sample

The subject population consisted of one healthy male. The test subject is working on the project and has studied human gait, giving him an understanding of the risks involved with participation. His participation was voluntary and he had the opportunity to quit at any time.

Description of Walkways

An adjustable track was used. It measures 9.14 m in length and 76.2 cm wide. The surface is smooth, made of plywood. The track is capable of making a transverse plane slope of 0-15°. For the study measurements were taken at 0 and 13°. 5.1 m down the track an area was removed to hold an AMTI Force Plate (Newton, MA), which was centered on the track. A wedge was used on the force plate when the track was sloped for the surface on the force plate to match that of the track.

Data Collection

The Peak Motus (Peak Performance Technologies, Inc) was used to capture and analyze all data. The test subject wore 15 reflective markers placed over the body according to the Peak template. Measurements were taken to determine the parameters of the subject and recorded as required by Peak Motus. The subject was allowed to walk the track until he felt comfortable. Five walking trials were performed for both the level track and sloped track. Four cameras, placed as recommended by Peak, captured video of each trial. The force plate recorded the forces on the downhill (left) foot.

Data Processing

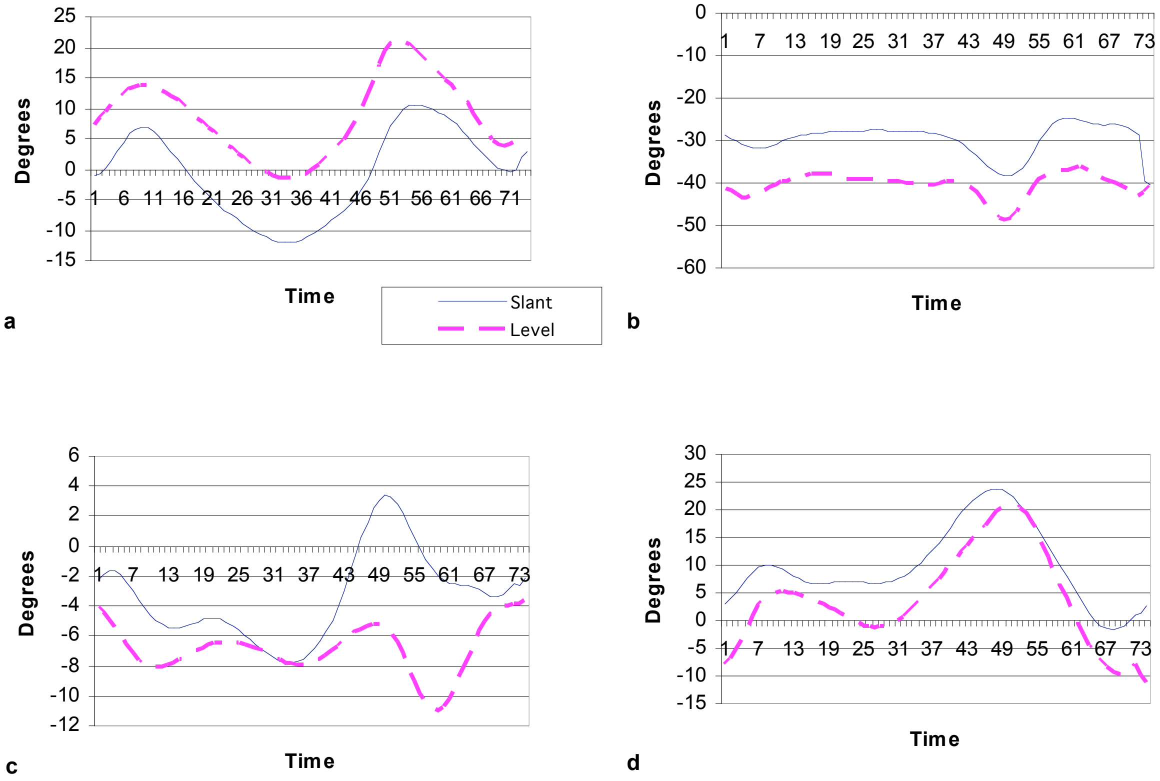

FIGURE 1. Joint kinematic data for the (a) ankle abd/add angles, (b) ankle int/ext angles, (c) knee abd/add angles and the (d) knee int/ext angles. Data taken from the average anles from the five trials at each track condition. Only data showing significant differences from level to sloped gait are shown. Angles are shown in degrees and time in

The ground reaction forces (GRF) measured by the force plate were sampled at 1200 Hz and the kinematic data were captured at 60 Hz. All data were synchronized by the Peak Motus video analysis system. Marker position was also found using Peak. The events of heel strike and toe off were identified to determine the stride length.

All data was evaluated using the Peak Motus Kinecalc formula engine. This creates moving 3-D models and calculates joint kinematics, resultant GRF and joint kinetics. Standardized statistical methods were used to analyze the data. Level flat surface is taken as the referent condition. These data are also compared to kinematics and isokinetic data of the normal knee to verify generalizability. Points of interest from each trial were taken and averaged. The data from the sloped surface trials were compared against the level surface trails with a t-test to show any significant differences.

RESULTS

Joint Kinematics

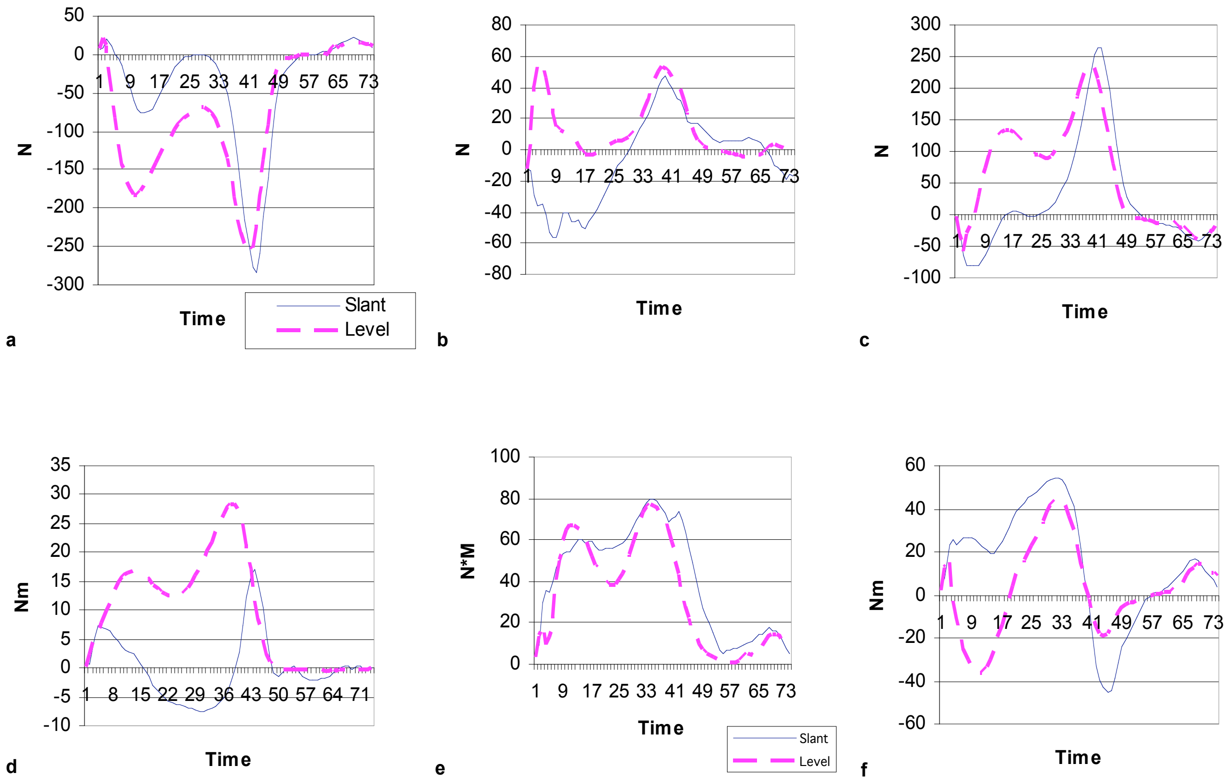

FIGURE 2. Joint kinetic data for the (a) ankle prx/dist force, (b) knee med/lat force, (c) knee ant/pst force, (d) ankle int/ext moment, (e) knee resultant moment and (f) the knee flx/ext moment. Data was taken from the average of the five trials at each track condition. Only data showing significant differences from level to sloped gait are shown. All forces are displayed in newtons (N) and moments in Newton-meters (Nm). Time is in centiseconds.

Joint kinematic data are presented in Figure 1. A significant grade effect was observed for the ankle abduction/adduction, ankle internal/external, knee abduction/adduction and knee internal/external angles. Measured angles of the ankle showed differences in only the interior-exterior (int/ext) and abduction-adduction (abd/add). The angle changes were equivalent but the sloped trials measured approximately 8° less than the level trials. The knee interior-exterior (int/ext) angles held a higher magnitude on the sloped trials by a magnitude of about 5°. The knee abduction-adduction (abd/add) angles followed a similar trend throughout the stride with the slanted gait being more toward the abduction by a magnitude of 2° until the propulsion phase where the angles measured -5° (level) and 3° (slanted). The toe-off phase angle minimums measured -11° (level) and -3° (slanted).

Joint Forces

There was a significant grade effect for the ankle in the proximal-distal (prx/dist) direction and for the knee in the medial-lateral (med/lat) and anterior-posterior (ant/pst) directions (Figure 2). In all cases, the forces were similar during propulsion and the toe-off phase of the stride. During the heel strike and braking phases the forces showed large differences. The knee med/lat forces are opposite at heel-strike for slant and level gait, level reaching 57 N in the medial direction and the sloped reaching 59 N in the lateral direction. The knee ant/pst forces were in the posterior direction for both trials initially (level-50 N, slope-75 N), then at the peak of the braking phase the level gait had an anterior force of 130 N, while the sloped gait only reached 5 N.

Joint Moments

The knee flexion-extension (flx/ext), knee resultant and ankle int/ext moments showed significant differences in the sloped verse level gait data (Figure 2). The ankle int/ext moments follow the same trend for the different slopes, the level having an internal moment 10-20 Nm more than the sloped gait during the heel-strike and braking phases. The ankle int/ext moments are similar for the propulsion and toe-off phases. The knee flx/ext moments reached an extension of 40 Nm during the braking phase for the level gait while during sloped gait the knee experienced a flexion moment of 25 Nm. During the propulsion phase of the knee an extension moment was felt for both trials with magnitudes of 20 Nm (level) and 45 Nm (sloped). The knee resultant moments appear similar, however the sloped moment didn't drop between peaks as did the level and the sloped gait appears to have a propulsion moment with a longer duration.

DISCUSSION

This research has been performed to test the methods described above. To understand the efficacy of the methods the recorded data has been analyzed below.

Joint Kinematics

The level gait analysis gave results similar to those found in the literature (Rose, Vaughan, 1992). The kinematic data helped validate the proposed methods as giving accurate data.

The difference in ankle abd/add angles was expected. This is due to the need of the foot to rotate in order to sit flat on the walking surface. The ankle int/ext angles for sloped gait were more toward the interior than the level gait by 10°. This may be because when rotated internally the ankle doesn't need to flex as far during the push-off. The ankle flx/ext angles were similar for both conditions, to maintain the same angles for the sloped gait the ankle needed to rotate uphill (interior). During the propulsion phase the knee was abducted 8° more for sloped than level gait. The reaction force caused by friction of the foot on the ground, which prevents sliding down the track, causes a moment which may cause the knee abduction angle. The knee abduction angle during sloped gait may cause a greater loading on the lateral meniscus during the propulsion phase. The increased loading may lead to degradation over time. The difference in the knee int/ext angles is a result of the ankle rotation. When the foot rotated uphill the entire leg must rotate, 10° of rotation in the ankle and an additional 5-10° in the knee.

Joint Forces

The level gait joint forces agreed with data reported in literature (McIntosh, 2005, Rose, Vaughan, 1992). This supports the validity of the proposed methods, as accurate kinetic data was obtained.

The level data for the ankle prx/dist forces showed a stronger distal force during the braking stage. This may be caused by the tendency to be more careful when walking on the slope in an attempt to maintain balance. This would cause a greater force on the uphill leg. The larger force of the sloped gait during the propulsion phase may be due to the need to raise the uphill leg higher than during level walking. The lateral force of the sloped gait during the braking phase is caused by the adducted position of the ankle. The adducted ankle pulls the tibia laterally, putting a force on the knee.[4] The greater knee posterior force during the beginning of the braking phase for the sloped gait may be caused by the caution used while stepping to avoid slipping on the slope. The level gait shows an anterior force shortly after heel-strike, while the sloped gait takes almost triple the amount of time (14 centiseconds) to change from a posterior to anterior force. The level walking is more aggressive during the braking phase while more force is applied by the sloped gait during the propulsion phase.

Joint Moments

The measured moments for the level trials were similar to data reported in literature (Lay, 2005, McIntosh, 2005, Vaughan, 1992). The proposed methods are valid for investigating gait on a level surface.

The ankle int/ext moment is caused by the angle the foot makes with the tibia. When the foot is oriented to the exterior, an interior moment is applied to the ankle pushing it in line with the motion of the gait. During sloped gait, the interior moment is of a small magnitude and the transition from braking to propulsion phases causes an exterior moment. As the weight leaves the heel and toe loading occurs, the weight of the body is over the heel and has the tendency to slide downhill, the external moment resists the internal rotation of the ankle as the toe would stay fixed and the heel would slide down slope.

The knee experiences an extension moment during the braking phase to catch the body's weight during level walking. During sloped gait the body's weight is carefully placed during the braking phase, leaving no need for the knee to absorb the shock of the weight, which explains the flexion moment during the braking phase for sloped gait. The leg is almost fully extended to reach the downhill side of the slope, which forces the knee to flex to prepare for the propulsion phase where extension is required. The knee extension moment during the propulsion phase again shows the aggressive nature of the propulsion phase during sloped walking, while the braking phase of level walking is more aggressive.

The knee resultant moments differ only slightly for the track conditions. The differences were found in the transition from braking to propulsion and in the duration of the propulsion phase. The sloped gait moment doesn't reach as high of a magnitude during the braking phase, yet didn't decrease as much as the level moment during the transition phase. The level trials showed moments reaching a higher magnitude during braking and decreasing by a much larger magnitude (~15 Nm) before the propulsion phase. Again this could be due to the careful walking done on the slope. A steady, lesser magnitude is applied to help create stability, then the propulsion phase maintains the peak magnitude for a longer time period. This moment duration may be prolonged by the need to elevate the uphill leg higher in order to start the next step.

Future Research

The methods appear to be effective for the level gait analysis. Additional pilot studies should be performed to demonstrate repeatability. A larger population should be tested. After obtaining a larger sample of data, additional statistical analysis can be done to determine the validity of the methods to this research.

Additional methods should be tested for the wedge on the force plate. The wedge used didn't apply a uniform force on the force plate, which may have tainted some of the date. The force plate should also be tilted and calibrated to measure forces while on the slope to compare data to the trials with the wedge.

After additional pilot studies have been completed and the final methods developed, research can begin on walking on different ballast to determine the affects of walking surface on gait dynamics.

ACKNOWLEDGEMENTS

This work is supported by the Ergonomics and Safety Lab at the University of Utah under the advisory of Donald Bloswick. Thanks to Andrew Merryweather for advice and help throughout the study.

REFERENCENCES

Andres, R.O., K.G. Holt, K.G., Kubo, M., "Impact of railroad ballast type on frontal plane ankle kinematics during walking", *Appl Ergon*. 36: 529-34. 2005.

Federal Railroad Administration, Railroad Safety Statistics, Annual Report 2004, US Department of Transportation. 2005.

Hunt, A.E., Smith, R.M., Torode, M., "Extrinsic muscle activity, foot motion and ankle joint moments during the stance phase of walking", *Foot Ankle Int*. 22: 31-41. 2001.

Kawakami, H., et al., "Gait analysis system for assessment of dynamic loading axis of the knee", *Gait Posture*. 21: 125-30. 2005.

Lay, A.N., et al., "Characterization of a system for studying human gait during slope walking", *J Appl Biomech*. 21: 153-66. 2005.

Lay, A.N., Hass, C.J., Gregor, R.J., "The effects of sloped surfaces on locomotion: a kinematic and kinetic analysis", *J Biomech*. 39: 1621-8. 2006.

McIntosh, A.S., et al., "Gait dynamics on an inclined walkway", *J Biomech*, 2005.

Rose, J. and J. Gamble, Human Walking.

Schwameder, H., Lindenhofer, E., Muller, E., "Effect of walking speed on lower extremity joint loading in graded ramp walking", *Sports Biomech*. 4: 227-43, 2005.

Vaughan, C.L., Dynamics of Human Gait 2nd Edition, C. Davis, Editor, 1992.