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Kinematics and kinetics of gait on stilts: Identification of risk factors associated with construction stilt use

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This study investigated kinematics and kinetic strategies and identified risk factors associated with gait on stilts. A six-camera motion-analysis system and two force platforms were used to test 20 construction workers for straight walking or turning, with or without carrying tools while wearing safety shoes or stilts at different heights. The results indicated that gait on stilts is characterised by increases in stride length, step width and the percentage of double support period, decreases in cadence, minimum foot clearance and a weaker heel-strike and push-off. Stilts place greater joint loadings on lower extremities to compensate for the added weight and limitation in joint mobility. Smaller foot clearances found for gait on stilts constitute an increased risk for tripping over obstacles. Workers may need to avoid prolonged use of stilts to alleviate stresses on the joints. This study was conducted to determine to what extent stilts alter the gait strategies and to explain the compensatory movements. Prior to this study, there has been little substantive research to evaluate the stresses and potential injuries associated with stilts.

Keywords: gait; stilts; construction; balance; tripping

1. Introduction

Human gait requires an integration of a complex neuromuscular-skeletal system and the coordination of muscles acting across many joints. The coordination and balance of gait could be disturbed by traumatic injury, neurological damage, gradual degeneration and even fatigue (Winter 1991). Dynamic balance of human gait can also be challenged by perturbations arising from environmental changes, i.e. floor slipperiness and compliance, or job-task requirements, such as working at heights (Wang *et al.* 1997, Redfern *et al.* 2001, Chiou *et al.* 2003, Bhatt *et al.* 2006).

Stilts are elevated tools that raise workers above the ground level to allow them to perform tasks on the ceiling or the upper half of a wall at residential or commercial building construction sites. Tasks performed with stilts include painting, plastering, insulation installation, acoustical ceiling installation or light-duty building maintenance. Modern stilts are composed of more than 50 small parts, providing mobility for workers to move from one location to another. Walking on stilts is an unstable task because stilts

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raise the centre of gravity of the body. The dynamic balance of construction workers on stilts is often further challenged by negotiating a curved path or by carrying tools or materials in the hands.

The use of stilts has been recognised as a high-risk activity that may lead to loss of balance and falls (Schneider and Susie 1994, Pan *et al.* 1999, Chiou *et al.* 2000, Whitaker 2006). In a US study of Washington State workers' compensation data for the period of 1996 to 2002, stilts-related injuries resulted in a median of 73 lost workdays compared to 24 lost workdays for all claims combined (Whitaker 2006). A survey of carpenters and drywall installers revealed that workers perceived the greatest fall potential and physical stress to be associated with the use of stilts, when compared to other elevated tools – scaffolds and ladders (Pan *et al.* 1999). A study on hazards in building construction hypothesised that stilts may place workers at increased risk for knee injuries and increases the likelihood of trips and falls (Schneider and Susie 1994). The state of California, USA, and the province of Ontario, Canada, have established legislation against the use of stilts as a preventive measure against occupational accidents. Beyond the perceived risks that might result from the use of stilts, however, no quantitative and objective data exist to demonstrate the hazards that might be associated with stilts.

Research in gait biomechanics has provided kinematic and kinetic understanding on level, ramp and stair walking in terms of ground reaction forces, joint moments and underlying mechanisms (Kadaba *et al.* 1990, Redfern and Dipasquale 1997, Wang *et al.* 1997, Vaughan *et al.* 1999). Gait on stilts has not been thoroughly investigated, perhaps due to their limited use by the general public. However, stilts are commonly used by construction workers. Their use in construction tasks is primarily to replace the need to position and move ladders and scaffolds and to allow workers to reduce the amounts of time they need to complete tasks using raised arm positions.

This study was undertaken to better understand the kinetic and kinematics aspects of gait associated with stilt use. An improved knowledge based on objective biomechanical aspects of stilt walking will permit the development of evidence-based guidelines for safe use of stilts by construction workers. The objective of this study was to quantify how stilts affect workers' gait patterns, body motions and dynamic balance. The effects of turning and tool carrying were also examined. The hypotheses were: (1) joint demands at hips, knees and ankles (e.g. peak joint moments) increases when walking on stilts; (2) there are differences in gait characteristics, e.g. cadence, stride length, stride width, stance period and foot clearance, with and without wearing stilts; (3) carrying tools in the hands and/or while negotiating a turn on stilts is associated with increased lower extremity joint loadings.

2. Method

2.1. Subjects

A total of 20 healthy male construction workers (mean age 35.8 ± 7.7 years) with more than 12 months of experience (mean 9.5 ± 7.7 years) in using stilts participated in the study. All subjects gave informed consent and underwent a health-history screening with the following exclusion criteria: history of dizziness; tremor; vestibular disorders; neurological disorders; cardiopulmonary disorders; diabetes; chronic back pain; individuals who have fallen within the past year resulting in an injury with days away from work. In addition, any subjects with body weights over 102.2 kg, exceeding the weight limit set by stilt manufacturers, were disqualified. On the day of the experiment, prior to the test, subjects were skill-tested by walking on stilts at 1.02 m (40 inches) height. Anyone

who did not demonstrate the ability to walk at least 6 m (20 ft) steadily without momentary alternation in gait or progressing with hesitation was excluded. Of all subjects, only one subject became ineligible due to body weight and one other was excluded for an inability to walk steadily.

2.2. Experimental design

Each subject underwent 12 randomised gait trials under a combination of three experimental conditions: stilt; walking path; and tool carrying. The stilt conditions were 0 m (no stilts), 0.61 m (24 inches) on stilts or 1.02 m (40 inches) on stilts. For test conditions of walking path, subjects walked on a 12 m (40 ft) straight path or half navigated the same straight path then turned 45° to the left onto another 4.6 m long path. For test conditions of tool carrying, subjects walked with or without holding a mud pan (0.5 kg) in their left palm and a trowel (0.3 kg) in the right hand.

The stilts used for the current study weigh 7.3 kg (16 lbs) and they are adjustable from 0.61 m to 1.02 m. The stilt shoe plate was strapped on to the bottom of the workers' shoes with a strut tube running up the side of the leg and strapped right below the knee (Figure 1). Two lower strut tubes connect the shoe plate with a nylon floor plate. The lower tubes are spring loaded to provide forward and rearward stilt walking actions.

2.3. Experimental procedures and laboratory setup

The experimental protocol was approved by the institutional human subject review board. On the day of the experiment, after providing informed consent, subjects put on tight-fitting clothing and safety shoes provided by the laboratory. A modified Helen Hayes marker system was applied with a total of 15 reflective spherical markers placed on specific anatomical locations (Kadaba *et al.* 1990). Eight additional markers, four on each side, were placed on the stilts (Figure 1). Anthropometric data (Table 1) were collected, which

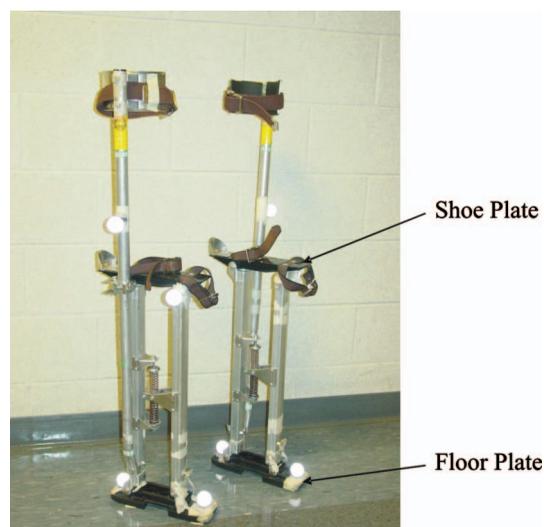


Figure 1. Stilts used for the study with four reflective markers attached to each side.

Table 1. Anthropometric measurements (n = 20).

Parameter	Mean	SD
Height (m)	1.8	0.2
Total body mass (kg)	80.9	10.7
Anterior superior iliac spine breadth (cm)	27.2	2.9
Thigh length (cm)		
Left	44.4	2.5
Right	44.6	2.0
Mid-thigh circumference (cm)		
Left	50.0	7.0
Right	50.6	6.9
Calf length (cm)		
Left	40.2	2.5
Right	40.3	2.9
Calf circumference (cm)		
Left	36.8	2.7
Right	37.0	2.8
Knee diameter (cm)		
Left	9.0	1.2
Right	9.1	1.2
Foot length (cm)		
Left	30.7	1.0
Right	30.7	1.0
Malleolus height (cm)		
Left	10.6	0.8
Right	10.7	0.8
Malleolus width (cm)		
Left	7.5	1.6
Right	7.4	1.7
Foot breadth (cm)		
Left	9.8	0.9
Right	9.9	0.9

are needed for calculating body segment parameters and for predicting joint centres and segment endpoints.

Subjects were tested along a walkway using a six-camera motion analysis system (Peak Motion Analysis SystemTM; Peak Performance Technologies, Englewood, CO, USA) at 60 Hz. Two force platforms (KistlerTM, Type 9287 and 9287A; Kistler Instrument Corp., Amherst, NY, USA) embedded in the walkway (Figure 2) were used to measure ground reaction forces at 600 Hz to produce joint kinetic information using inverse dynamics. Subjects were required to walk from point A and travelled to (1) point B, C and D or (2) points B and C and then turned left to point E (Figure 2). The order of test conditions was randomised for each subject. They were asked to walk in a self-selected manner at a comfortable speed. The starting position was adjusted in order to ensure that each foot hit one and only one force plate naturally. Practice trials were performed prior to the test sessions to ensure proper stepping and cadence. Trials with mis-stepping were eliminated and the trial was repeated. For carrying tasks, subjects walked in the same manner while holding a mud pan and a trowel in their hands. All subjects wore the same model of safety shoes (Iron AgeTM model 604; Iron Age Corporation, Pittsburgh, PA, USA) with polyvinylchloride soles and steel toes before donning stilts, as well as for trials without stilts.

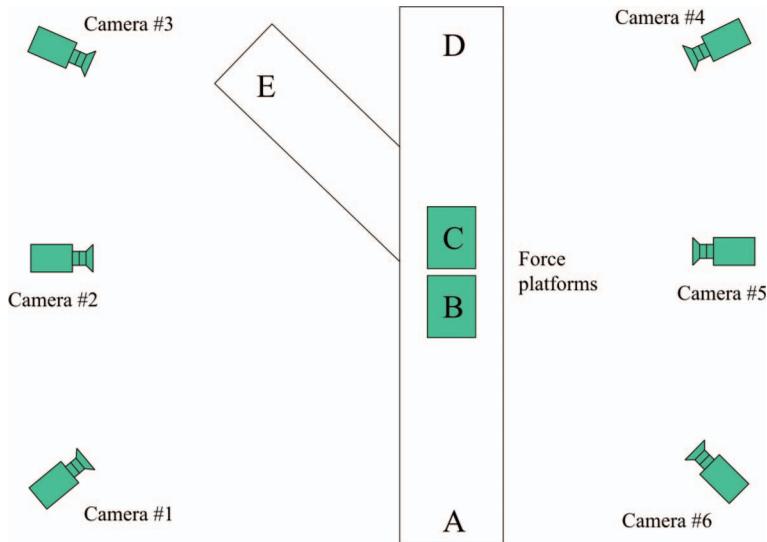


Figure 2. Laboratory layout of walkway, motion cameras and embedded force platforms.

2.4. Dependent variables

Four groups of dependent variables were examined to comprehensively evaluate the stilts from different perspectives – gait characteristics (i.e. gait speed, cadence, stride length, etc.), ground reaction forces, lower extremity joint angles and joint moments. Gait characteristics provide information on the spatio-temporal differences between gait with safety shoes and stilts, whereas ground reaction forces reflect the force impacts applied by shoes or stilts to the floor. Information on joint angles reveals the possible posture changes due to stilts. Knowledge of the joint moments were used to explain how the work is distributed among the different joints, thereby enabling a more complete understanding of balance mechanism for gait on stilts. To better understand if there are risks of tripping, minimum foot clearances during mid-swing were also evaluated.

Gait characteristics included cadence (steps/min), speed (m/s), step width (m), stride length (m), stance period (%) and double stance period (%). The step width was defined as the medial–lateral distance between two heel markers on the shoes or the floor plates of stilts. The stance and double stance period was calculated as the percentage of time during a gait cycle when one foot/stilt or both feet/stilts contact with the floor, respectively.

Ground reaction force variables include peak forces in vertical and medial–lateral directions. The braking forces and propulsive forces, representing the peak forces in the first and second half of stance in the anterior–posterior directions were also included in the analysis. Joint angles include ankle plantarflexion/dorsiflexion, knee flexion/extension and hip flexion/extension, as well as ranges of motion in the sagittal plane. Joint moment variables include the peak moments of force calculated about the centre of rotation of the ankle, knee and hip joints in the sagittal plane.

In this study, the minimum foot clearance during mid-swing phase was used as an indicator for trip-related falls (Winter 1992, Begg *et al.* 2007). The foot clearance was measured as the vertical distance between the toe marker and the floor. For gait with safety shoes, the toe marker was placed on top of the safety shoes, directly above the second metatarsal head. For gait with stilts, the toe marker was placed on the front part of

the stilt floor plate. Since the thicknesses of shoe sole and stilt floor plate are different, the vertical height of toe marker captured by the motion analysis system was adjusted before the comparisons were made. Using the angle formed by the floor and the line connecting toe and heel markers, the thicknesses of the shoe sole and stilt floor plate in 3-D space during the gait cycle were considered.

2.5. Data analysis

Both gait with or without stilts were modelled as multi-body systems that were solved using the inverse dynamics approach. The stilts were treated as two extended body segments – left and right stilts. The contact force between the stilt and ground was considered as the boundary forces in the analysis and they were transferred to the foot/stilt segments. The contact force between the foot and the stilts was treated as the internal forces in inverse dynamics. The 3-D coordinates of each marker were filtered using Butterworth at cut-off frequency of 6 Hz. Anthropometric measurements as listed in Table 1 were used in regression equations to predict the masses and moments of inertia of lower extremity segments (Kadaba *et al.* 1990, Vaughan *et al.* 1999).

The current study concentrated on the sagittal plane motions since it is the plane where the most movements occur. Internal joint moments for the hip, knee and ankle were normalised to each subject's body weight. Peak hip and knee flexion/extension angles and moments and peak ankle plantar-/dorsi-flexion angles and moments were extracted from each subject's gait data. The ground reaction force data were also normalised to the subject's weight.

Multivariate repeated measure ANOVA (MANOVA) models were first performed to simultaneously test the effect of within-subject factors (stilt, path, tool) and interactions on four groups of variables – gait characteristics (i.e. speed, cadence, step length, etc.), ground reaction forces, joint angles and joint moments. Based on the results of MANOVA, the effect of stilt was found to be highly significant on all four groups of variables ($p < 0.0001$). The main effect of turning was significant on ground reaction forces ($p < 0.002$) and gait characteristics ($p = 0.001$). Univariate ANOVA were then performed for each independent variable. For any significant main effect, multiple comparisons were performed using Tukey's HSD method to determine the different levels of the independent variables. The level of significance was set at $p < 0.05$.

3. Results

3.1. General gait parameters

Table 2 shows the general gait parameters for three different stilt conditions. During gait with safety shoes (no stilts), subjects' cadence (97.3 steps/min) and speed (1.25 m/s) were within normal limits (91–135 steps/min and 1.1–1.82 m/s) for the general population (Whittle 2002). Subjects' average walking speed was significantly reduced from 1.25 m/s for safety shoes to 1.08 m/s and 1.03 m/s for 24 inch and 40 inch height on stilts, respectively ($p < 0.001$). Significant lower cadence (81.2 vs. 84.9 steps/min) and walking speed (1.03 vs. 1.25 m/s) were also observed for turning path compared with straight path ($p < 0.001$).

Subjects' mean step width was 15 cm for gait without stilts and it was significantly increased to as much as 25 cm on stilts ($p < 0.0001$). The stride length was significantly increased from 1.55 m for safety shoes to 1.71 m to 1.75 m on stilts ($p < 0.001$), but it was

Table 2. Gait cycle parameters.

	Stilt Condition			Path	
	No stilts (safety shoes)	24-inch stilts	40-inch stilts	Straight	Turn
Cadence (steps/min)	97.3 (7.5)	75.8 (6.4)	70.9 (7.1)	84.9 (14.3)	81.2 (12.5)
Speed (m/s)	1.25 (0.16)	1.08 (0.15)	1.03 (0.16)	1.25 (0.16)	1.03 (0.14)
Step width (m)	0.15 (0.05)	0.24 (0.08)	0.25 (0.10)	0.21 (0.08)	0.22 (0.10)
Stride length (m)	1.55 (0.15)	1.71 (0.22)	1.75 (0.24)	1.82 (0.20)	1.53 (0.16)
Stance period (s)	0.76 (0.05)	0.93 (0.21)	1.04 (0.10)	0.90 (0.21)	0.92 (0.14)
Stance period (%)	60.7 (3.0)	60.0 (2.8)	60.6 (3.9)	60.5 (3.5)	60.7 (3.2)
Double stance period (%)	20.0 (2.1)	21.6 (3.5)	22.6 (3.3)	20.6 (3.5)	21.5 (2.9)

Note: Standard errors are shown in parenthesis.

still within the normal gait limits (1.25–1.85 m). Significantly shorter stride length was observed for turning paths (1.53 m) compared to straight paths (1.82 m) ($p < 0.001$).

With regard to temporal variables, significantly longer stance period was observed for gait on stilts ($p < 0.02$). The percentages of double stance period for gait at 24 inch (21.6%) and 40 inch stilts (22.6%) were found to be significantly greater than that of safety shoes (20.0%). A greater percentage of double stance period was also found for gait on a turning path (21.5% vs. 20.6%) compared to a straight path ($p < 0.02$). The increase in the percentage of double stance period relatively decreases the percentage of single stance period.

3.2. Ground reaction forces

The ground reaction force pattern during walking on stilts preserved typical features observed during normal walking without stilts. Figure 3(a,b,c) illustrates the ground reaction forces for three stilt conditions as a function of stance time. The vertical forces show a characteristic double-peak pattern with the first peak resulting from an acceleration of the body's centre of gravity during early stance, followed by a reduction in force as the body moves over the supporting leg in mid-stance (Whittle 2002). The second peak was due to push-off and decelerating downward motions in late stance (Whittle 2002). It was noticed that the vertical force patterns for gait on stilts at 24 inch and 40 inch were relatively flat during mid-stance, in contrast with an exaggerated dip for normal gait on level ground without stilts. The peak-to-peak differences in vertical forces (magnitude differences between the first and second peaks) were 0.76 N/kg and about 0.48 N/kg for safety shoes and stilts, respectively ($p < 0.05$).

The anterior/posterior ground reaction forces demonstrated a braking force impulse in the first half and a propulsive impulse during the second half of the stance phase (Figure 3(b)). The fore–aft force pattern for stilt walking was generally similar to normal gait. However, there was a 52% decrease in mean braking force and a 42% decrease in mean propulsive force for 40 inch stilts compared to no stilts. Repeated ANOVA reaffirmed that gait with stilts resulted in significantly smaller braking and propulsive forces than normal walking ($p < 0.001$). No significant changes in braking and propulsive forces were detected between the two levels of stilts. The magnitudes of medial and lateral components of force for stilts were small with the general force pattern similar to that of safety shoes.

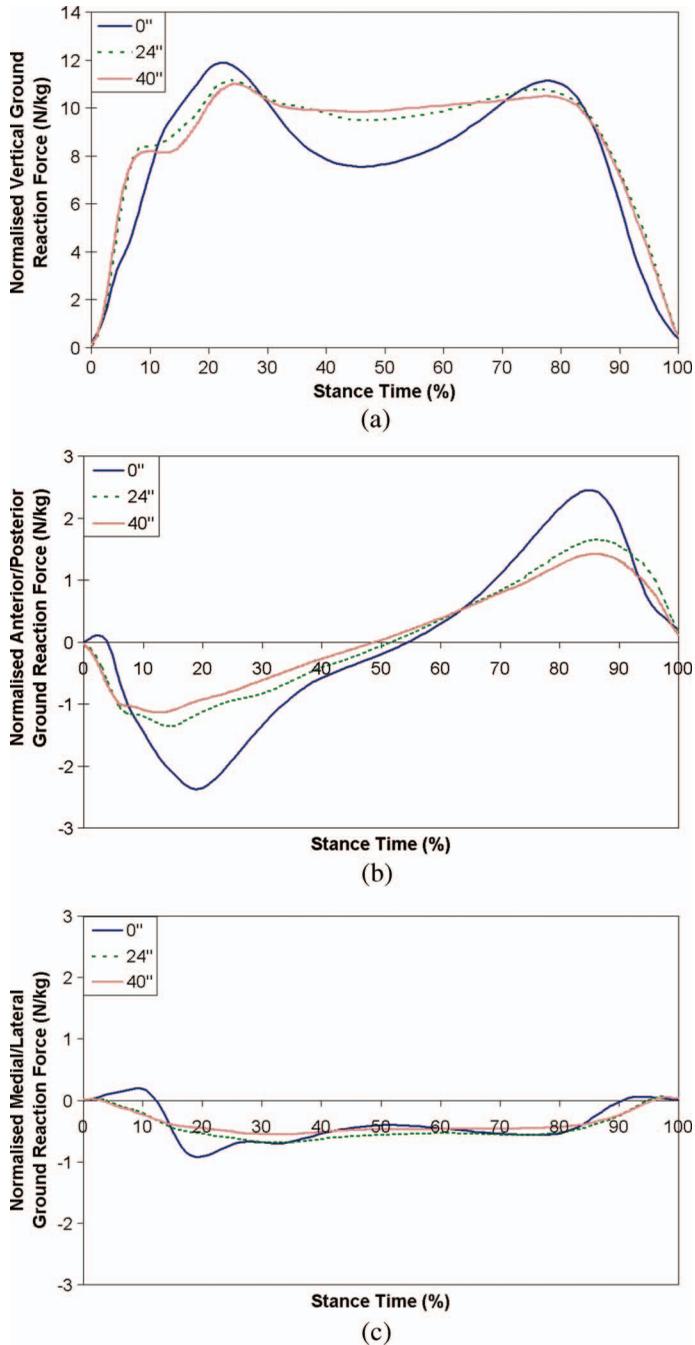


Figure 3. Ground reaction forces for three stilt conditions averaged over all subjects: (a) vertical ground reaction forces; (b) anterior/posterior ground reaction forces; (c) medial/lateral ground reaction forces. The first foot contact (heel strike) was associated with 0% and the last foot contact (prior to toe off) of the same foot was with 100% of total contact time.

3.3. Kinematics

3.3.1. Joint angle

Considerable differences were observed when comparing lower extremity joint angles between gait with and without stilts. The hip flexion/extension, knee flexion/extension and ankle dorsi-/plantar-flexion angles are shown in Figure 4(a,b,c), respectively. The effect of stilts was found to be significant for peak hip extension, knee flexion and ankle plantar-flexion angles ($p < 0.0001$). Although the shapes of the hip and knee joint angle curves were similar for three stilt conditions, the ranges of motion for gait on stilts were significantly reduced ($p < 0.0001$). As the height of stilt increased from 24 inch to 40 inch, hip and knee ranges of motion as well as the peak hip extension and knee flexion angles decreased (Figure 4(a)). There were 13.6 and 25.5° decreases in hip and knee ranges of motion during the gait cycle for 40 inch stilts compared to normal gait. The major change in hip motions was the decrease in hip extension during terminal stance and pre-swing phases in stilt walking (Figure 4(a)). Subjects' knee flexion was increased by more than 14° at heel strike. The most noticeable difference in knee motions was the 14 and 18° decrease in the mid-swing (70–85% of gait cycle) for 24 inch and 40 inch stilts, respectively. The ankle joint angle profiles were completely different from normal walking with a characteristic of no plantar-flexion.

3.3.2. Foot clearance

Subjects' minimum foot clearances during mid-swing phase were found to be distinctly related to the stilt condition ($p < 0.0001$). Figure 5 illustrates the foot clearance as a function of the gait cycle. In general, the foot clearances for stilt conditions were consistently lower than those of no stilts throughout the entire gait cycle. The minimum foot clearances during mid-swing were 1.80 cm, 1.12 cm and 0.82 cm for safety shoes, 24 inch stilts and 40 inch stilts, respectively. The minimum foot clearance for safety shoes was significantly greater than that of 24 inch or 40 inch stilts ($p = 0.01$). There was an approximate 1 cm reduction during mid-swing when the stilt swings directly beneath the body. No significant differences in minimum foot clearances were found between the two levels of stilts.

3.4. Joint moments

Despite the similar joint moment patterns among the three stilt conditions (Figure 6(a,b,c)) at hip, knee and ankle joints, peak joint moment values differed in the weight acceptance and pre-swing phases of the gait cycle. During the stance phase (0–60% of gait cycle), differences were observed in the hip, knee and ankle joint moments due to stilt wearing. Immediately after initial foot contact, there were sudden and quick increases in hip extension, knee extension and ankle dorsi-flexion moments. The increases in this first peak joint moments between safety shoes and 40 inch stilts were 0.19 N-m/kg (19%), 0.16 N-m/kg (30%) and 0.32 N-m/kg (110%) at hip, knee and ankle joints, respectively. As the foot progressed to 50% of gait cycle in the pre-swing phase, another increase in peak joint moments was found. This second peak hip and knee flexion moments between safety shoes and 40 inch stilts were 0.41 N-m/kg (56%) and 0.16 N-m/kg (28%), respectively. The differences in the second peak joint moments were insignificant for ankle joints.

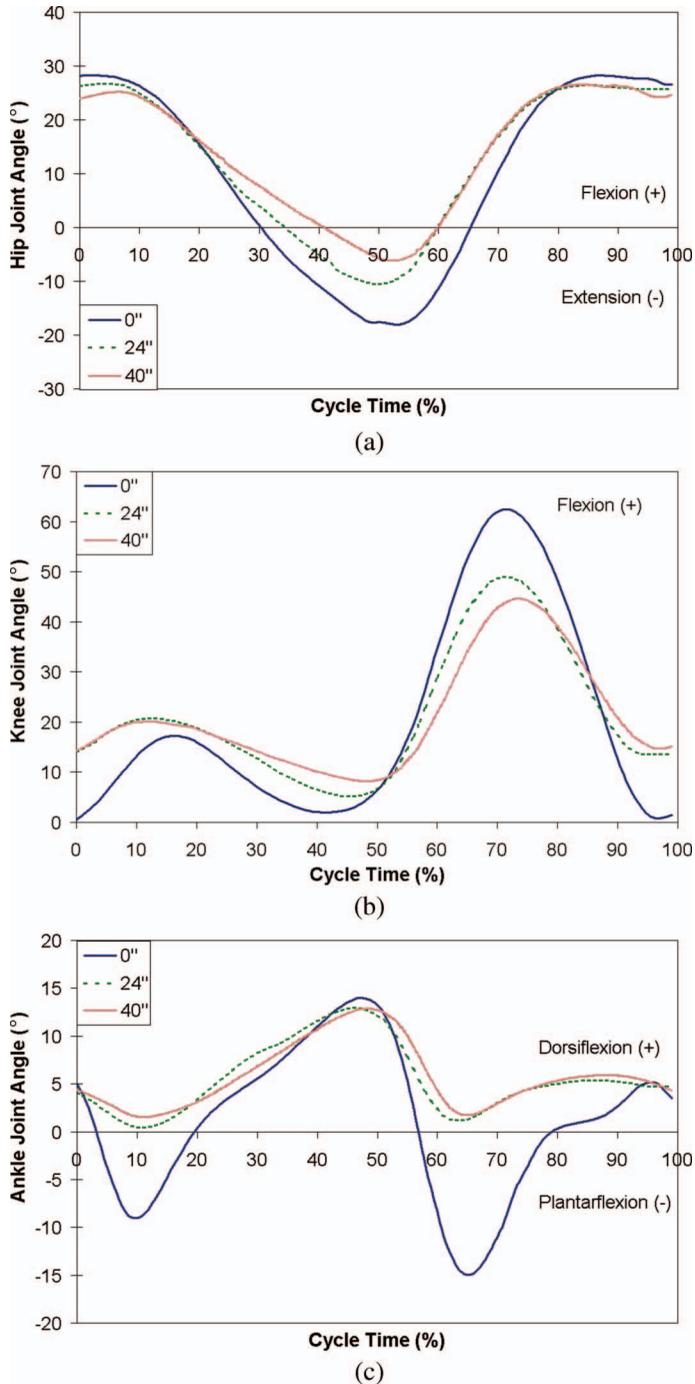


Figure 4. Joint angles for three stilt conditions averaged over all subjects: (a) hip flexion (+)/extension (-) angle; (b) knee flexion (+) angle; (c) ankle dorsi (+)/plantar (-) flexion angle. Joint angles were normalised to the gait cycle with the first foot contact at 0% and the second heel contact of the same foot at 100% of gait cycle.

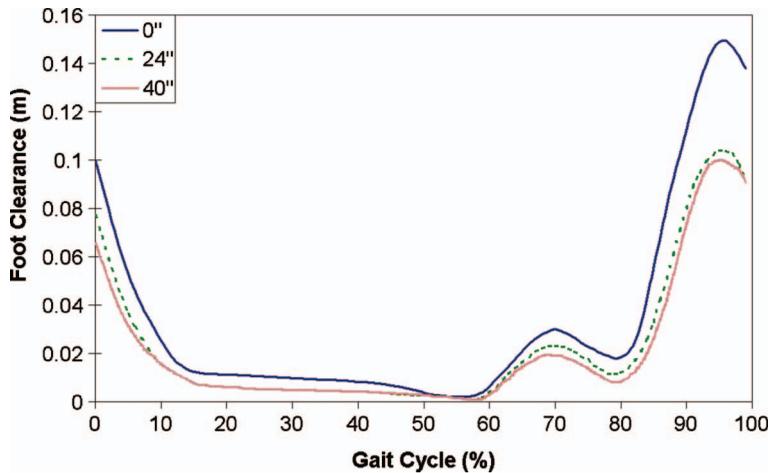


Figure 5. Foot clearance for three stilt conditions over a gait cycle.

3.5. Effect of path and tool carrying

There was no effect found on ground reaction forces and joint moments due to tool carrying. However, the tool effect was significant on peak hip flexion and extension angles ($p < 0.05$), but not on knee and ankle motions in the sagittal plane. Tool carrying resulted in greater hip flexion at heel strike as well as greater peak hip flexion during the gait cycle. The mean hip flexion and extension for tool carrying were 36.4° (vs. 28.1°) and 16.6° (vs. 13.6°), respectively.

Spatio-temporal adjustments were observed during negotiating a turning path. Turning is accomplished by decreasing walking speed (1.23 m/s vs. 0.98 m/s; $p < 0.0001$) and stride length of the left foot (1.78 m vs. 1.47 m; $p < 0.001$) and increasing the percentage of double stance period (21.5% vs. 20.6%; $p < 0.03$). Turning also resulted in a decrease in the anterior–posterior ground reaction forces and the decrease was more drastic on stilts, as dictated by a significant stilts and path interaction ($p < 0.0001$). On the other hand, turning increased the medial–lateral ground reaction force. The increase was less extreme on stilts, also indicated by stilts and path interaction ($p < 0.001$).

The only noticeable change in joint angles due to turning was the decrease in left knee flexion, for the inner limb while making a left turn (52.6 vs. 54.5° , $p < 0.008$). Stilts and path interactions on peak joint moments were observed for ankle plantar-flexion and knee flexion moments ($p < 0.001$). As the stilt height increased from 24 inch to 40 inch, knee and plantar-flexion moments were more pronounced for a straight path. There were 65% increases in knee flexion moments from normal walking at 40 inch stilts on a straight path, while only a 32% increase for a turning path. A similar trend was found for ankle plantar-flexion moments with 70% and 50% increases between normal walking and 40 inch stilt walking for straight and turning paths, respectively.

4. Discussions

The primary objective of the present study was to explore how gait on stilts is accomplished by investigating the kinematics and kinetics of the lower extremity while walking on stilts. Knowledge of the joint motions and moments of the lower extremity and

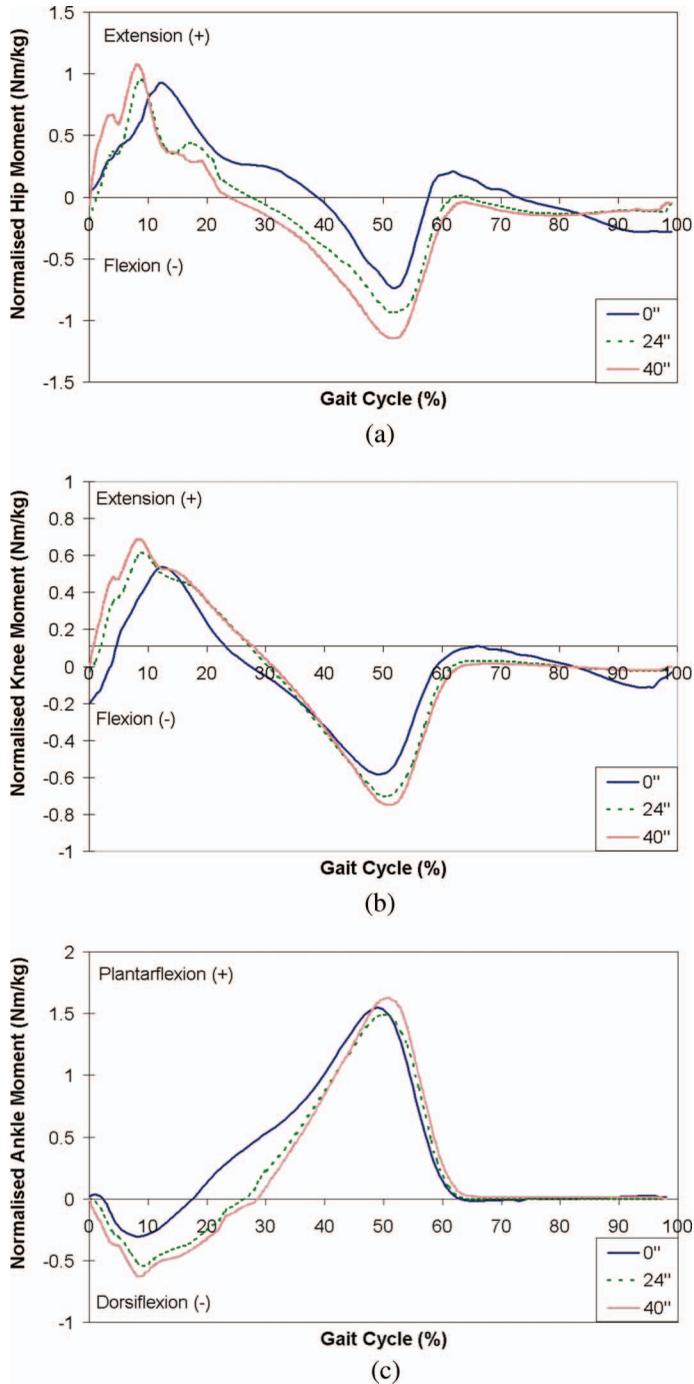


Figure 6. Joint moments for three stilt conditions averaged over all subjects: (a) hip extension (+)/flexion (-) moment; (b) knee extension (+)/flexion (-) moment; (c) ankle planter (+)/dorsi (-) flexion moment. Joint moments were normalised to the gait cycle with the first foot contact at 0% and the second heel contact of the same foot at 100% of gait cycle.

gait adjustments while walking on stilts is helpful for the understanding and identification of risk factors associated with stilts. Findings from this study support the hypotheses that peak lower extremity joint moments are increased when stilts are in use and confirmed the spatio-temporal differences between gait with and without stilts. However, the hypothesis that carrying tools and negotiating a turn are associated with increased joint loadings is rejected.

Gait on stilts is characterised by increases in stride length, step width and double stance period (%), decreases in cadence and foot clearance and a weaker heel-strike and push-off. Such functional changes in gait represent adaptations adopted by workers in order to maintain dynamic balance on stilts. The primary adaptation is the increase in percentage of double stance time to give the body a longer period to re-establish stability from one step to another. Associated with the prolonged double support period was a significant decrease in percentage of single stance period. This decrease minimises the time period when only one foot is in contact with the floor while the other foot is swinging through (Winter 1991). The considerable increase in step width, a 67% increase, is needed to maintain balance by maximising the base of support. Stilts raise the centre of gravity of the body, thus potentially diminishing the stability of equilibrium. The subjects appeared to adjust their gait to compensate for this change by increasing the double stance period (%) and widening their step, to maintain walking stability.

The ground reaction force profiles, representing the summation of mass-acceleration products of all body segments while the foot or stilt is in contact with the floor, revealed the cause of specific walking patterns that were observed in the experiment. The small peak-to-peak forces in the vertical direction and braking and propulsive forces in the anterior–posterior direction for gait on stilts may result from the slow speed of walking. The distinct speed-related changes of the ground reaction force profiles were reported in previous research with peaks of the reaction forces correlated to the velocity of walking (Andriacchi *et al.* 1977, Whittle 2002). The notable reduction in braking and propulsive forces signifies the less vigorous heel contact and weaker push-off.

The hip and knee angle profiles were similar in curve shapes in general except for the small ranges of motion associated with gait on stilts. The restricted range of motion is an indication of stiff joints as a result of 7.3 kg of extra weight attached to the feet and straps around the feet and knees. The most restricted joint was ankles with 56% to 61% decrease in range of motion, followed by knees (29–41% decrease) and hips (20–30% decrease). Workers were not able to effectively extend hips, flex knees and plantar-flex their ankles on stilts. The knees were flexed to about 62.4° during normal walking but only 44.6° during the swing phase on taller stilts. In particular, the angular changes of ankles during the weight acceptance and swing phases were largely reduced, with no plantar-flexion observed. The ankles were dorsi-flexed throughout the entire gait cycle to keep feet on stilts and sustain the weight of stilts. The loss of active plantar-flexion indicates that ankle muscles cannot provide an active push-off during the pre-swing phase. This finding correlates with the weak push-off in the low propulsive force profile and signifies a less 'dynamic' gait pattern with low speed and less control of walking (Winter 1991). Postural balance on stilts was further challenged using taller stilts as the ranges of motion for hip and knee joints were significantly decreased.

The patterns of joint moment curves for gait on stilts are similar to those of normal gait with safety shoes; however, the peak joint moments were significantly greater on stilts. The most pronounced differences in joint moments were the high magnitudes of ankle dorsi-flexion moments during weight acceptance and hip flexion moments during pre-swing. Although joint moments represent the net muscular, ligament and friction forces

acting on the joints, they are mainly provided by muscles (Winter 1991). Ankle and hip muscles appear to play dominant roles in modulating the joint loadings to compensate for the weight of stilts and the increased balance demands during early and late stance, respectively. The high ankle dorsi-flexion moments were needed to ensure a successful landing, while the high hip flexion moments in late stance were needed for propulsion of the body forward and upward. As the height of stilts increased from 24 inch to 40 inch, except for the hip flexion moment during late stance, hip extension moment and knee and ankle joint moments remained unaffected, with no significant statistical difference detected. The increased hip flexion moments were needed possibly for accelerating the body in the upward and forward directions at a higher setting of stilts. In contrast, the muscular demands at knees were not as high as hips or ankles, with 30% to 28% increase in peak knee extension and flexion moments in the early and late stance on stilts. The increases in joint moments also suggest that lower extremities – particularly hips and ankles – were exposed to great joint forces, which may predispose workers to premature joint degeneration (Hurwitz *et al.* 2001, Royer and Wasilewski 2006). Studies on osteoarthritic gait have demonstrated a link between abnormal joint loading and knee osteoarthritis (Sharma *et al.* 1998, Kaufman *et al.* 2001). The significant increase in joint moments and the percentage of double stance period could also be interpreted as signs that gait on stilts is a particularly challenging task for the neuromuscular system (Royer and Wasilewski 2006). Any unexpected perturbations arising from environmental changes or job task demand, such as slippery surfaces, excessive arm reach, negotiating a sharp turn, etc., may disturb dynamic balance.

Walking on stilts, like normal gait, requires sufficient foot clearance of the swing limb as well as the stability of the body supported primarily by the stance limb. Findings from this study demonstrate significantly smaller minimum foot clearances during mid-swing phase of gait on stilts, which is considered to constitute an increased risk for tripping in previous gait studies (Winter 1992, Begg and Sparrow 2000, MacFadyen and Prince 2002, Begg *et al.* 2007). Problems with foot trajectory can result from many factors in the segment-link chain, including stance limb, pelvis and swing limb (Winter 1991). In the present study, the small foot clearance on stilts could come from insufficient knee flexion during swing phase, excessive knee flexion during stance phase and the mechanism of the stilt floor plate. Due to the restricted joint motions and the weight of stilts, subjects did not pick up their feet as high as they would for normal gait. Consequently, they were more likely to hit an object on the floor, if any existed. Locomotion at construction sites often requires negotiating a cluttered and unpredictable environment. Successful navigation through the construction sites requires effective avoidance of obstacles and securing adequate footing (Krell and Patla 2002). Small foot clearances during gait on stilts are more likely to result in unsuccessful obstacle avoidance at the job site and lead to loss of balance. The risks of tripping are even greater as workers on stilts may not visibly detect obstacles on the floor.

In this study, tool carrying did not result in any significant effects on joint moments, which could be attributable to the light weight of tool that subjects carried. The differences in hip motions due to tool carrying may be because subjects were unable to use arm swings to counterbalance trunk rotation. The spatio-temporal adjustments and changes in horizontal ground reaction forces when negotiating a turn were consistent with previous studies that turning is achieved by the decrease in stride length of the inner limb, the increase in the medial-lateral ground reaction forces and the deceleration in forward motion (Davis 1983, Hase and Stein 1999, Orendurff *et al.* 2006). To make a turn, the forward momentum is reduced before rotating the body and stepping out toward the new

plane of progression. Negotiating a turn accentuates the differences between gait with and without stilts. It is interesting to note that muscular demands reflected by knee flexion moments and plantar-flexion moments for a straight path were greater than those of a turning path. This phenomenon could be attributable to the substantial increase in transverse and frontal moments required in making a turn, as reported by previous studies (Nyland *et al.* 1997, Colby *et al.* 2000). In contrast to normal gait, the relatively drastic decrease in sagittal moments on stilts suggests an increased dependence on the transverse and frontal moment generation needed to assist the body in changing toward the new direction (Chiou *et al.* 2006). Further analysis on frontal and transverse plane joint moments is needed to verify the control mechanism for turning on stilts.

5. Conclusions

Findings from this study provide insights on the important aspects of gait characteristics and kinematics and kinetic mechanisms by which gait on stilts is accomplished. First, stilts appear to place greater demands on lower extremities to compensate for the limited joint motions as a function of restriction by the binding straps of the stilts as well as by the weight of stilts abnormally loading the limbs. The peak hip extension, knee flexion, knee extension and ankle dorsi-flexion moments increased during gait on stilts. Second, in comparison with normal gait, significantly smaller minimum foot clearances during mid-swing were found on stilts, which is considered to constitute an increased risk for tripping in previous gait studies (Begg *et al.* 2007). Third, experienced workers, as observed from this study, were able to adjust their body movements and alter their gait to carry out their tasks while on stilts. Gait adaptations were adopted to compensate for the restriction in joint motions and weight of stilts by increasing the percentage of double stance period and step width and decreasing the walking speed. Nevertheless, their ability to detect perturbations and trigger the reactive mechanism may be diminished due to lack of sensory feedback and restricted body motions. Finally, ankles and hips appear to play dominant roles in modulating the joint loadings to carry out tasks while on stilts. Workers may need to limit the prolonged use of stilts, especially at high elevation, to alleviate the burdens on the joints and reduce muscle fatigue arising from increased muscle activities required to maintain balance. In addition, workers should inspect the work environment before putting on stilts, to ensure the floors are free of obstacles, such as cables, wires or cut pieces of drywall.

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