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Analysis of Musculoskeletal Loadings in Lower Limbs During Stilts Walking in Occupational Activity

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Abstract—Construction workers often use stilts to raise them to a higher level above ground to perform many tasks, such as taping and sanding on the ceiling or upper half of a wall. Some epidemiological studies indicated that the use of stilts may place workers at increased risk for knee injuries or may increase the likelihood of trips and falls. In the present study, we developed an inverse dynamic model of stilts walking to investigate the effects of this activity on the joint moments and musculoskeletal loadings in the lower limbs. The stilts-walk model was developed using the commercial musculoskeletal simulation software AnyBody (version 3.0, Anybody Technology, Aalborg, Denmark). Simulations were performed using data collected from tests of four subjects. All subjects walked without or with stilts through a 12-m straight path. The moments of the knee, hip, and ankle joints, as well as forces in major muscles or muscle groups in the lower limbs, for stilts walking were compared with those for normal walking. Our simulations showed that the use of stilts may potentially increase the peak joint moment in knee extension by approximately 20%; induce 15% reduction and slight reduction in the peak joint moments in ankle plantar flexion and hip extension, respectively. The model predictions on the muscle forces indicated that the use of stilts may potentially increase loadings in five of eight major muscle groups in the lower extremities. The most remarkable was the force in rectus femoris muscle, which was found to potentially increase by up to 1.79 times for the stilts walking compared to that for the normal walking. The proposed model would be useful for the engineers in their efforts to improve the stilts design to reduce musculoskeletal loadings and fall risk.

Keywords—Gait, Stilts, Muscle forces, Inverse dynamics, Joint moment.

INTRODUCTION

There were an estimated 23,540 overexertion injuries that involved days away from work in the construction industry in 2007.[22] The study indicated that drywall installers were ranked fourth highest among all construction occupations in term of workers' compensation due to injuries.[5,9,21] Their compensable injury rate was almost three times the average for all construction occupations combined.[21] Sprains, strains, and/or tears counted for more than 40% of all injuries of drywall installers.[5] Nearly 20% of the total cases incurred an injury to the lower extremity, with injuries mainly on the legs and ankles. The knees were the most frequently injured body parts of the lower extremities among drywall installers, and often resulted in 10 or more days away from work.[5] Overexertion injuries were responsible for the greatest proportion of costs for medical care, permanent impairment, and paid lost days.[13] Musculoskeletal injuries in the lower limbs in drywall installers are likely related to the operation procedures and tools used.

Stilts are commonly used for drywall installations at construction sites. With stilts, construction workers are raised to a higher level above ground and are able to perform tasks (such as taping and sanding) on the ceiling or upper half of the wall. Chiou *et al.*'s[4] tests on construction workers indicated that experienced construction workers tend to walk more slowly using stilts compared with the normal walking. In a separate study, however, stilts walking was found to be faster than the normal walking for stilts users in sports or leisure activities.[24] The higher speed was due to the increased step length in spite of a decrease in step rate. It is not clear whether the use of stilts during walking increases musculoskeletal loading, thereby increasing the risk of musculoskeletal injuries in the lower limbs.

Schneider and Susi[20] hypothesized that the use of stilts may place workers at increased risk for knee injuries or may increase the likelihood of trips and falls. A survey of carpenters and drywall installers indicated that the workers using stilts perceived greater fall potential and physical stress than those using other elevated tools, such as scaffolds and ladders.[15,14] In a recent study of Washington State workers' compensation data for a period from 1996 to 2002, stilts-related injuries resulted in a median of 73 lost

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workdays compared to 24 lost workdays for all claims combined.[27] The state of California and the province of Ontario (Canada) have, therefore, established legislation against the use of stilts as a preventive measure for occupational safety. The effects of the stilts walking on the musculoskeletal loading and postural stability have not been analyzed.

Walking on stilts, the construction workers are typically elevated by 0.5–1.5 m (Fig. 1a). Due to the increased height and possibly faster walking speed, the postural stability in stilts walking will be more likely influenced by visual or psychological perturbations at work sites compared with the normal walking. Besides, the stilts add excessive mass moments of inertia to the lower limbs, requiring the stilt users to apply more effort during walking. Consequently, workers may require excessive forces in their lower limbs to maintain the postural balance when walking on stilts. All of these factors could contribute to cumulative trauma musculoskeletal disorders in the lower limbs of the construction workers.[11] The purpose of our study is to develop an inverse dynamic model of stilts walking to investigate their effects on joint moments and musculoskeletal loadings in the lower limbs. Specifically, the moments at the knee, hip, and ankle joints, as well as forces in major muscles or muscle groups in the lower limbs for stilts walking will be compared with those for normal walking. We hypothesize that the use of stilts in walking will increase the joint moments and muscle loadings in the lower limbs.

METHODS

Model of Stilts Walking

The stilts-walking model was developed using the commercial musculoskeletal simulation software AnyBody (version 3.0, Anybody Technology, Aalborg, Denmark) by modifying its existing three-dimensional gait model (Gait3D) (Fig. 2a). The three-dimensional gait model (Gait3D) includes only the lower body, i.e., two legs and pelvis. The hip, knee, and ankle joints were considered to have 3 DOFs (degree of freedom) (external/internal rotation, abduction/adduction, and extension/flexion), 1 DOF (extension/flexion), and 2 DOFs (plantar/dorsi flexion and eversion/inversion), respectively. The gait model includes a total of 70 muscles—35 muscles on each leg.

Each of these 70 muscles was simulated by a "classical" three-element muscle model,[12,30] consisting of a Hill-type contractile element, a parallel elastic element, and a series elastic element. The contractile element includes the force–length and force–velocity relationships, as well as the effects of the pennation angle. The parallel-elastic element is a nonlinear spring with its stiffness being governed by the passive

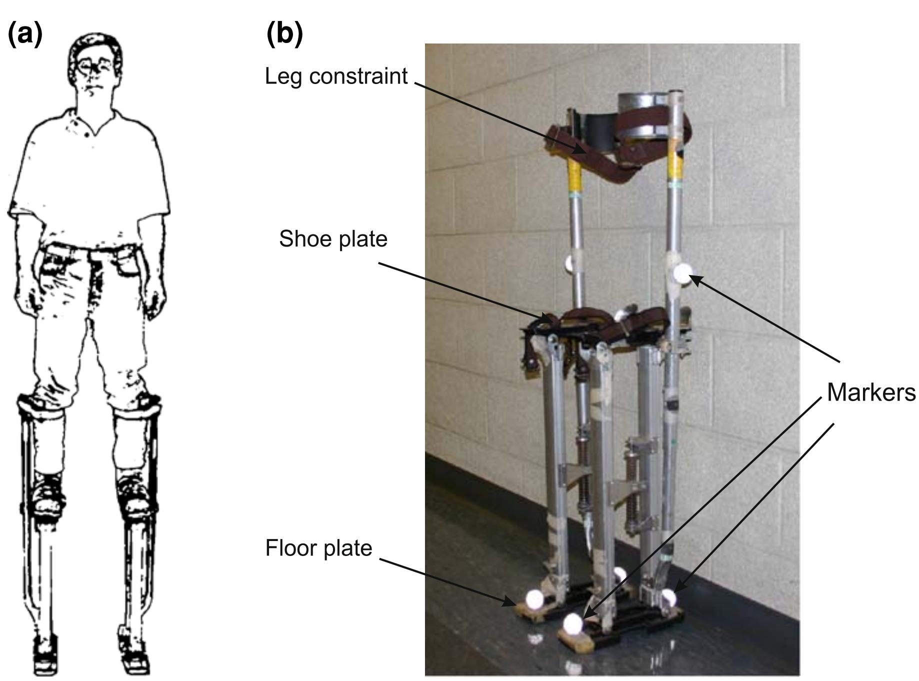

FIGURE 1. Stilts are used to elevate the workers by 0.5–1.0 m in construction sites. (a) A construction worker walking on stilts. (b) A pair of typical stilts used in constructions. The stilts used in the current study are made of aluminum and have an elevation height of 0.61 m. Motions of three markers on each stilt are collected in our tests: two on the foot plate (one front and one back) and one on the shoe plate.

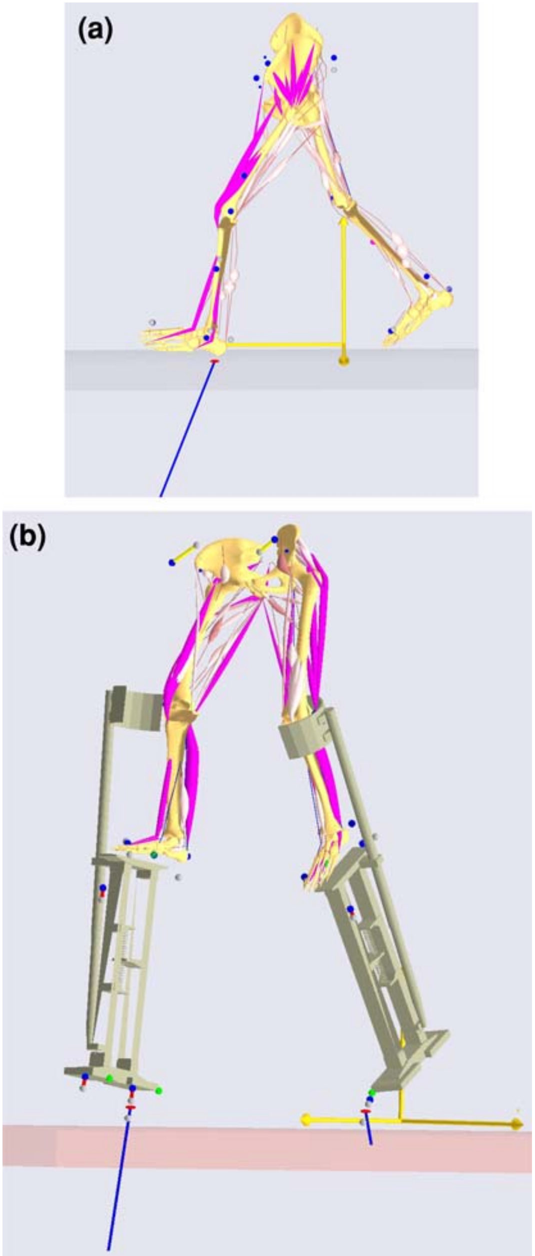

FIGURE 2. Gait modeling using commercial software package AnyBody. (a) Normal walking. (b) Stilts walking. The three-dimensional gait model includes only the lower body, i.e., two legs and pelvis. The model contains a total of 70 muscles—35 muscles on each leg. The subjects walk on a level ground during the tests.

force–length relationship of the muscle. The serial-elastic element mimics the nonlinear-elastic behavior of the tendon. The inverse dynamics computation scheme solves the kinematics of the problem first, which means that the current length and contraction velocity of the muscle is derived. From this, the muscle model computes the strength and passive forces in the muscle. The strength is used as a normalization factor in the optimization-based muscle recruitment problem,[18] and the passive forces enter the equilibrium equations on the right-hand side.

The muscle configurations and parameters were consistent with Delp.[8] The maximal isometric force was assumed to be 35 (N/cm^2) $\times$ physiological cross-sectional area (PCSA) (in cm^2).[10] Detailed model parameters (i.e., force–length curves and slack lengths for each tendon; force–length and force–velocity curves for each muscle; PCSA, optimal fiber length, and pennation angle at the unloaded state for each muscle) were adopted from the ISB data base (SL Delp: Parameters for a model of the lower limb. http://isbweb.org/data/delp/index.html). The mass moment of inertia of each body section (i.e., foot, shank, thigh, and pelvis) was estimated by considering the body sections as ellipsoidal cylinders with uniform mass density.[19,25] A uniform mass distribution on the body sections was applied in the 3D gait model.[25] The characteristics of the passive nonlinear-elastic behavior of the each muscle were considered to be identical in the model, because there are no sufficient published experimental data that can be used for determining these parameters.

The stilts used for the current study are commercially available for drywall finishers and painters (Dura-Stilts Ltd, Uckfield, UK). The stilts are made of aluminum and have an elevation of 0.61 m (i.e., the height from the foot to the floor plate, as shown in Fig. 1b). Each stilt has a mass of 3.64 kg and a total height of 1.02 m. A stilt was conceptually modeled using one single rigid segment, which has different mass moments of inertia in its three principal directions. The mass moment of inertia of the stilt was determined experimentally as described in the Appendix. In the model, the stilts were attached to the feet and lower legs (just inferior to the joint line at the knee). The feet were assumed to be constrained to the foot plates of stilts in all three translational directions. The stilts were attached to the lower legs of the human model via bushings (Fig. 2b), which were assumed to be linearly elastic springs with a constant stiffness and to carry tensile loading in lateral and anterior/posterior directions only. The bushing stiffness was estimated to be 100 N/mm.

The center of mass (CoM) of the stilts was determined using a hanging approach and was estimated to be at a height of 0.41 m from the bottom of the floor plate. Using swing tests, as described in Appendix (Fig. A1), the mass moments of inertia around the y and z-axis (I_{CY} and I_{CZ}) of the local coordinate were determined to be 0.95 and 1.27 kg m^2, respectively. Using Eq. (A7) and assuming an effective radius $R = 0.10$ m, the mass moment of inertia around the x-axis was estimated to be 0.02 kg m^2.

Determination of Kinematics of Normal and Stilts Walking

A total of 18 reflective spherical markers were placed on the lower extremities of the subjects, at anatomical landmarks, as suggested by Vaughan *et al.*[25] For the tests with stilts walking, three additional motion markers were placed on each stilt (Fig. 1b).

The marker kinematics were collected at 60 Hz using a six camera Peak Motus Motion Measurement System (Peak Performance Technologies Inc., Englewood, CO, USA). The kinematic data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 6 Hz. Two force platforms (Kistler, Type 9287 and 9287A, Kistler Instrument Corp., Amherst, NY, USA) embedded in the walkway were used to measure ground reaction forces at a frequency of 600 Hz. The force plates were placed adjacent to each other with a gap of 1/8 in (3.18 mm). The same force plate setup was used for both normal walking and stilts walking tests.

Test Protocol and Experimental Procedure

Four healthy construction workers [mean (±SD) age 35.8 ± 7.7 years] with more than 12 months of experience in using stilts participated in the study. The subjects have a mean height of 1.77 ± 0.03 m and a mean body mass of 79.5 ± 16.4 kg. All subjects gave informed consent and underwent a health-history screening. All subjects wore the same model of safety shoes (Iron Age model 604, Pittsburgh, PA, USA) with polyvinylchloride (PVC) soles and steel toes provided by the laboratory before donning stilts, as well as for trials without stilts.

Subjects walked without or with stilts through a 12-m straight path. When walking on the stilts, the subjects were elevated by 0.61 m from the floor. The subjects were asked to walk at a comfortable speed, step on the first force plate with their left foot (left foot heel strike), and take the subsequent step (right foot heel strike) on the second force plate. The starting position for the gait was slightly adjusted for each subject to achieve a left heel strike approximately at the center of the first force platform. This method ensures that the normal gait pattern is minimally modified by the restriction imposed by the placement of the force platforms on the walkway. Practice trials were performed at the beginning of each test session to ensure proper stepping and cadence.

Analysis Procedure

The simulations were performed using an inverse dynamic approach. The model was driven by the motion markers; and the ground reaction forces were applied as boundary conditions. The simulations were run twice. The first run was intended to calculate the joint moments. The simulations were performed by applying "universal joint muscles" on each joint. The "universal joint muscle" is a joint moment that is mechanically equivalent to the sum of the torques generated by the muscles on the corresponding joint. The obtained generalized muscle "force" in the simulations were the joint moments. In the second run, the three-element muscle models were applied and the time-histories of the muscle forces were obtained. Before each simulation, the model was calibrated to adjust the tendon lengths, such that each of the muscles worked around its optimum length range during the locomotion. The recruitment of the muscle forces was calculated by using a min/max optimization procedure in AnyBody,[18] in which the maximal normalized muscle force was minimized. Physiologically, such an optimization procedure is equivalent approximately to minimizing muscle fatigue.[7]

The effects of stilts walking on the kinematics and kinetics were analyzed by evaluating the time histories of joint angles, joint moments, and ground reaction forces. The effects of the stilts on the musculoskeletal loading were analyzed by comparing the time histories of muscle forces obtained for stilts walking with those for normal walking. To make our results comparable with those in literature,[2,23] we analyzed the muscle forces in eight muscle or muscle groups: soleus (SOL), gastrocnemius (GAS), gluteus maximus (GMAX), vastii, i.e., vastus lateralis, vastus medialis, and vastus intermedius (VAS), rectus femoris (RF), hamstring muscle group, which includes semitendinosus, semimembranosus, biceps femoris caput longum, and biceps femoris caput breve (HAMS), posterior gluteus minimus/medius (GMEDP), and anterior gluteus minimus/medius (GMEDA). Iliopsoas muscles were included in the model, but their results were not presented. Since both gluteus minimus and gluteus medius muscles consist of three muscles in each group in our model (i.e., posterior, medium, and anterior compartment), the forces in GMEDP and GMEDA muscle groups were estimated by:

$$F_{\mathrm{GMEDP}} = F_{\text{posterior minimus}} + F_{\text{posterior medius}} + \frac{1}{2}\left(F_{\text{medium minimus}} + F_{\text{medium medius}}\right) \tag{1}$$

$$F_{\mathrm{GMEDA}} = F_{\text{anterior minimus}} + F_{\text{anterior medius}} + \frac{1}{2}\left(F_{\text{medium minimus}} + F_{\text{medium medius}}\right) \tag{2}$$

in which, the medium gluteus minimus/medius were considered to contribute equally to the posterior (GMEDP) and anterior (GMEDA) muscle groups.

The loading levels of the muscles or muscle groups were evaluated by normalized muscle forces. The normalized muscle forces were calculated by dividing the actual muscle force by the maximal isometric force, which was estimated by the PCSA multiplied by a muscle strength factor (35 N/cm^2).

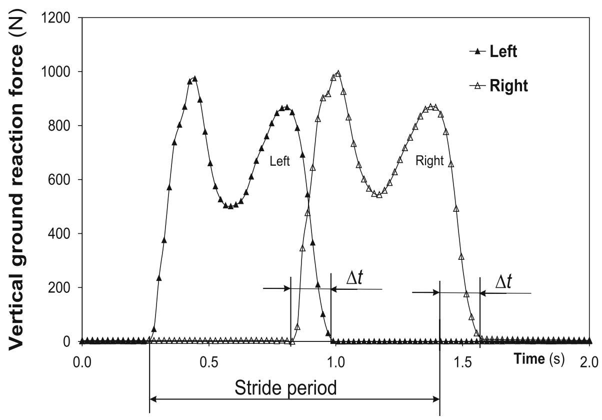

FIGURE 3. Ground reaction forces in vertical direction (*z*-axis) for left and right foot are applied to determine the stride period. The stride period is calculated as the time from left foot contact to right foot off, minus the double support phase, Δ*t*.

The time-histories of typical ground reaction forces recorded from left and right feet for a subject for normal walking are demonstrated in Fig. 3. The stride period, which is defined as the time period between two consecutive heel contacts on the ground for the same foot, is determined by the total feet/floor contact time minus one double support interval (Δ*t*), as illustrated (Fig. 3). For each test, we first determined the stride period from the plots of the ground reaction forces of left and right feet, all other parameters were then presented as a function of gait cycle. The mean gait cycle time for walking with and without stilts was 1.58 and 1.24 s, respectively.

RESULTS

In all results figures (Figs. 4–8), we plotted the means of the data obtained from four subjects and the

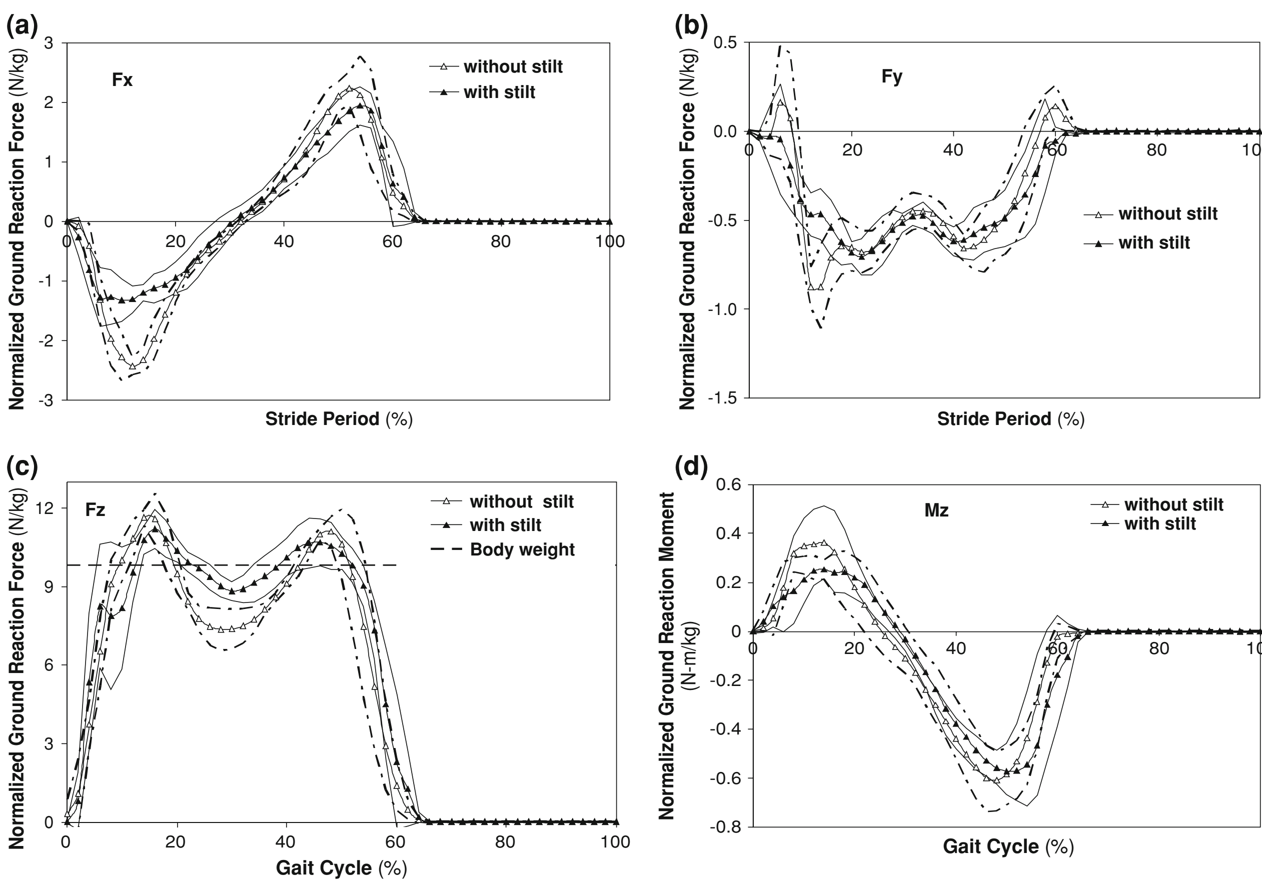

FIGURE 4. Comparison of the normalized ground reaction forces and moment for stilts walking with those for normal walking during one gait cycle. (a, b, c) Normalized ground reaction force in *x*-, *y*-, and *z*-direction, respectively. (d) Normalized ground reaction moment around *z*-axis. The ground reaction forces and moment are normalized by dividing the measured values by the body mass of the subject (in kg). The curves shown in these figures are the mean of the measurements collected from four subjects. The *doted* lines represent the 95% confidence intervals of the data for the normal walking, while the *thin solid lines* represent those for the stilts walking.

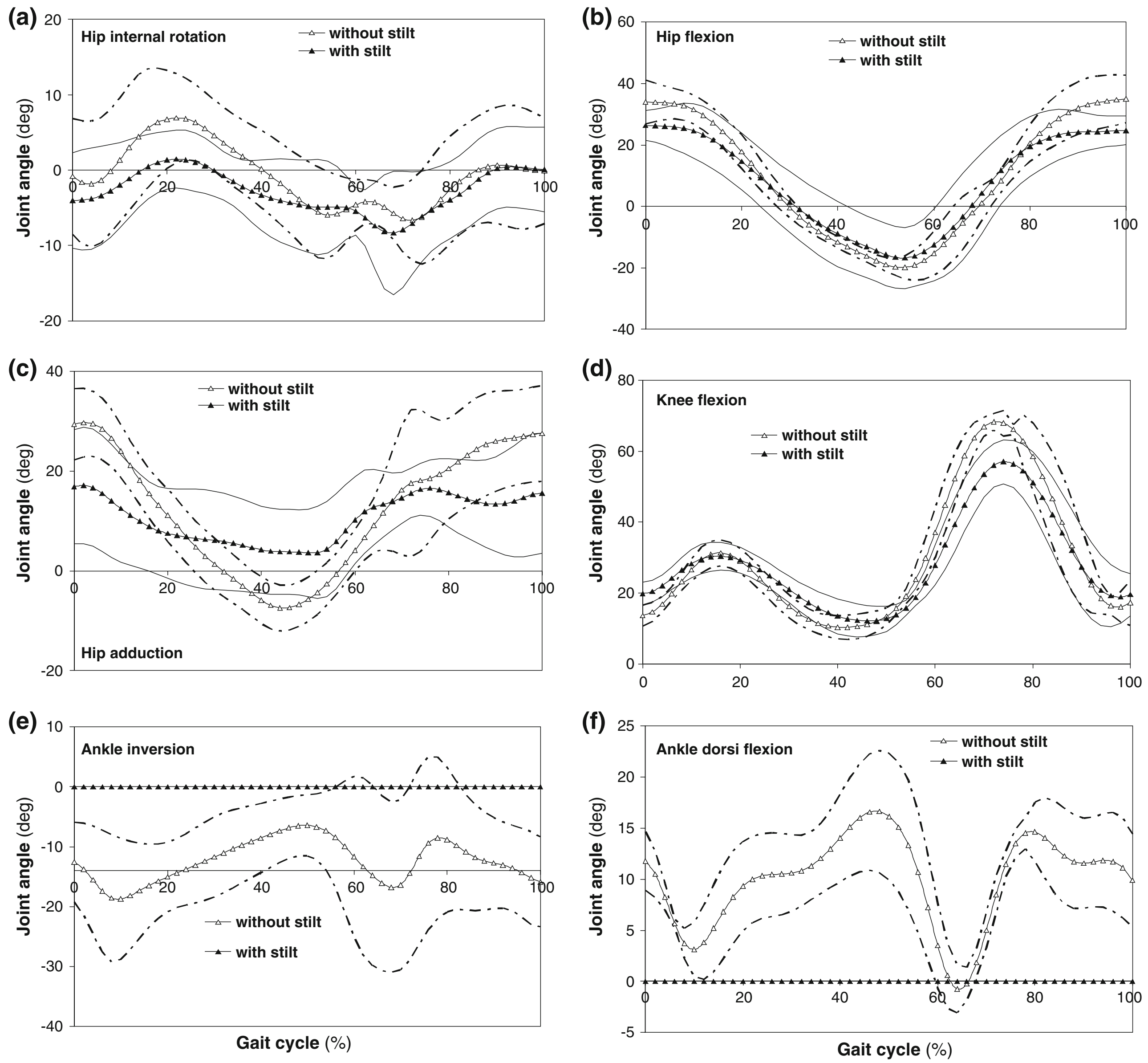

FIGURE 5. Comparison of the joint angles for stilts walking with those for normal walking during one gait cycle. (a, b, c) Hip internal rotation, flexion, and adduction, respectively. (d) Knee flexion. (e, f) Ankle inversion and dorsi flexion. The ankle joint motions are constrained in the model of stilts walking and, therefore, they are constantly zero. The curves shown in these figures are the mean of the data obtained from four subjects. The *doted lines* represent the 95% confidence intervals of the data for the normal walking, while the thin *solid lines* represent those for the stilts walking.

corresponding 95% confidence intervals (the doted lines for the normal walking and the thin solid lines for the stilts walking).

The normalized ground reaction forces in x, y, and z-axes, and the corresponding normalized ground reaction moment about z-axis are depicted in Figs. 4a, 4b, 4c, and 4d, respectively, for both normal walking and stilts walking. The ground reaction moments about x- and y-axis are zero and not shown. The vertical ground reaction forces (F_z) for both normal and stilts walking show a typical double-peak pattern, varying around the body weight, as described in the literature[29]; and the patterns for the horizontal ground reaction forces (F_x and F_y) as well as the ground reaction moment about the z-axis (M_z) for normal walking are found to be similar to those for stilts walking. In early stance, the magnitude of the peak ground reaction force in posterior direction (F_x) for normal walking is approximately 1.85 times that for stilts walking (Fig. 4a). During the middle stance, the vertical ground reaction force (F_z) for the stilts walk has a flatter pattern than that for the normal walk (Fig. 4c).

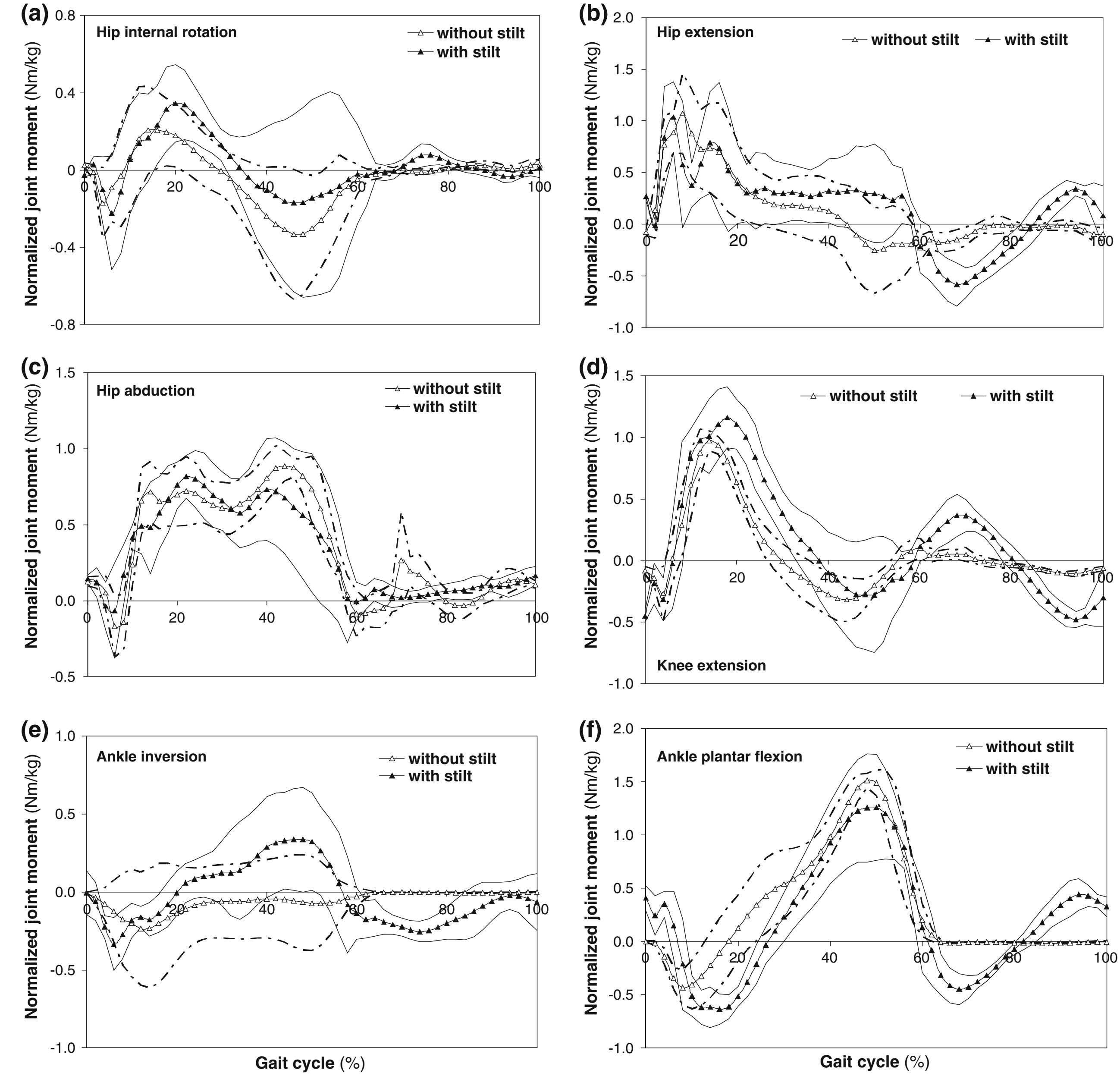

FIGURE 6. Comparison of the normalized joint moments for stilts walking with those for normal walking during one gait cycle. (a, b, c) Hip internal rotation, extension, and abduction, respectively. (d) Knee extension. (e, f) Ankle inversion and plantar flexion, respectively. The joint moments are normalized by dividing the computed joint moment values (in N m) by the body mass of the subject (in kg). The curves shown in these figures are the mean of the data obtained from four subjects. The *doted lines* represent the 95% confidence intervals of the data for the normal walking, while the *thin solid lines* represent those for the stilts walking.

The time histories of joint angles for stilts walking are compared with those for normal walk in Fig. 5. The range of motion (ROM) in the hip internal rotation for stilts walking is approximately 10 ± 6.1^0, which is approximately 30% less than that for the normal walking (13 ± 5.8^0). The ROM of the hip adduction for the normal walking (36 ± 5.9^0) is approximately 2.6 times that for stilts walking (14 ± 10.3^0). In the sagittal plane, the hip and knee flexion ROM for the normal walking are greater than those for the stilts walking by approximately 25 and 29%, respectively. In our model for the stilts walking, the ankle inversion and dorsi flexion were constrained (i.e., assumed to be zero), whereas they varied approximately in a range of 12 ± 7.8^0 and 17 ± 4.1^0, respectively, in normal walking (Figs. 5e and 5f).

The computed time-histories of the normalized joint moments for stilts walking are compared with those for normal walk in Fig. 6. The maximal joint moment was found in the ankle flexional motion and reaches a

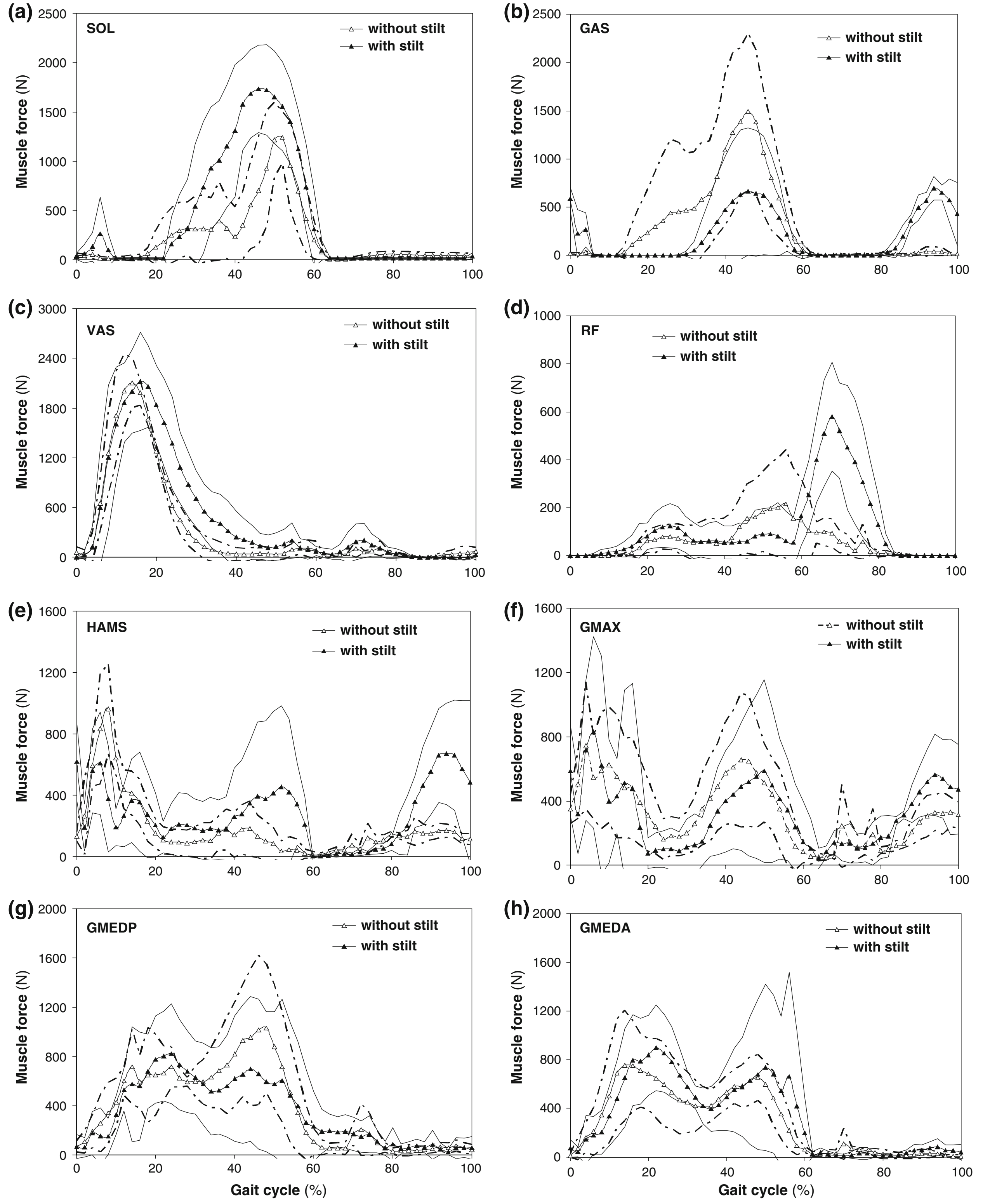

FIGURE 7. Comparison of the forces in eight muscles or muscle groups for stilts walking with those for normal walking during one gait cycle. (a) SOL (soleus), (b) GAS (gastrocnemius), (c) VAS (vastus lateralis, vastus medialis, and vastus intermedius), (d) RF (rectus femoris), (e) HAMS (hamstring, which includes semitendinosus, semimembranosus, biceps femoris caput longum, and biceps femoris caput breve), (f) GMAX (gluteus maximus), (g) GMEDP (posterior gluteus minimus/medius), and (h) GMEDA (anterior gluteus minimus/medius). The curves shown in these figures are the mean of the data obtained from four subjects. The *doted lines* represent the 95% confidence intervals of the data for the normal walking, while the *thin solid lines* represent those for the stilts walking.

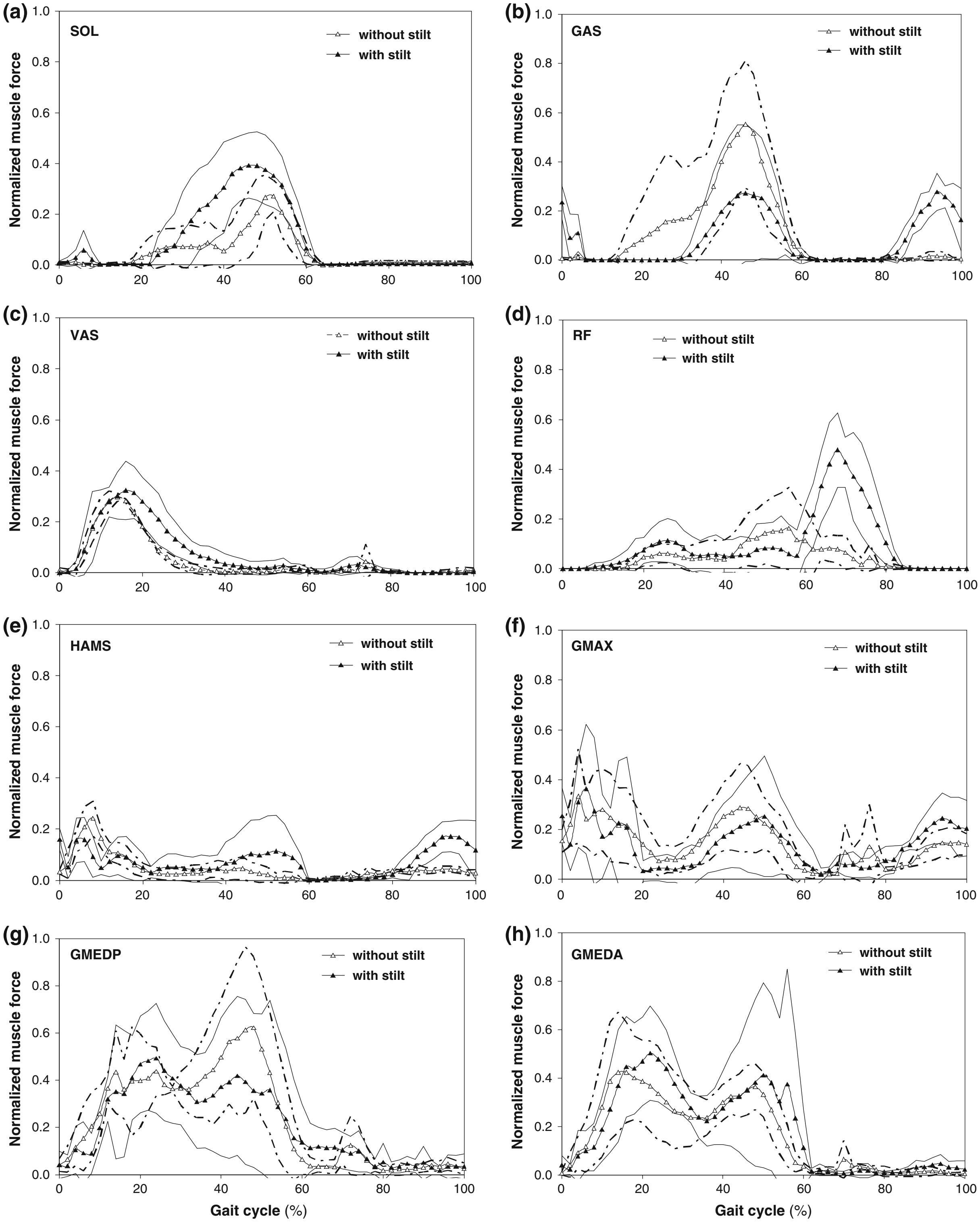

FIGURE 8. Comparison of the normalized forces in eight muscles or muscle groups for stilts walking with those for normal walking during one gait cycle. (a) SOL (soleus), (b) GAS (gastrocnemius), (c) VAS (vastus lateralis, vastus medialis, and vastus intermedius), (d) RF (rectus femoris), (e) HAMS (hamstring, which includes semitendinosus, semimembranosus, biceps femoris caput longum, and biceps femoris caput breve), (f) GMAX (gluteus maximus), (g) GMEDP (posterior gluteus minimus/medius), and (h) GMEDA (anterior gluteus minimus/medius). The muscle forces are normalized by dividing the computed muscle forces by the corresponding maximal isometric muscle forces. The curves shown in these figures are the mean of the data obtained from four subjects. The *doted lines* represent the 95% confidence intervals of the data for the normal walking, while the *thin solid lines* represent those for the stilts walking.

magnitude of approximately 1.5 ± 0.13 N m/kg at peak for the normal walking. It is seen that the use of stilts caused the peak joint moment to increase by approximately 25% in knee extension during loading response while to decrease by approximately 15% in ankle plantar flexion. The stilts use was found not to cause significant changes of the peak flexional joint moment in the hip. The peak joint moments in hip internal rotation and ankle inversion were found to increase approximately 55 and 35%, respectively (Figs. 6a and 6e, respectively), due to the use of stilts. However, these joint moments are relatively small in magnitude compared with the flexion/extension joint moments and are not predominant. The use of stilts was found to cause little variations in the peak joint moment of the hip abduction (Fig. 6c).

The computed time-histories of forces in eight muscles or muscle groups (SOL, GAS, VAS, RF, HAMS, GMAX, GMEDP, and GMEDA) for stilts walking are compared with those for normal walking in Fig. 7. The maximal peak muscle force was found in SOL (Fig. 7a), reaching approximately 1730 ± 453 and 1240 ± 266 N for stilts and normal walking, respectively. Among these eight muscles or muscle groups, the maximal peak muscle forces were found to increase in five muscle groups and to decrease in three muscle groups due to the use of stilts. The peak maximal muscle forces in SOL, VAS, RF, GMAX, and GMEDA (Figs. 7a, 7c, 7d, 7f, and 7h, respectively) were found to increase by approximately 40, 2, 150, 25, and 18%, respectively, for the stilts walking compared with the normal walking. The use of stilts induced a reduction of the peak maximal muscle forces in GAS, HAMS, and GMEDP (Figs. 7b, 7e, and 7g, respectively) by approximately 56, 30, and 20%, respectively.

The time-histories of the normalized muscle force for these eight muscle groups are depicted in Fig. 8. The trends of the effects of the stilts use on the normalized muscle forces are similar to those observed in the muscle force magnitudes (Fig. 7). GAS, GMEDP, and GMEDA muscles were relatively heavily loaded during the normal waling; the peak normalized forces in these muscles were predicted to be around 0.4–0.6. The RF muscle group was least loaded, the normalized muscle force reached merely 0.16 ± 0.17 at peak during the normal walking. The use of stilts induced substantial increases of the peak normalized muscle force in RF and SOL muscles (180 and 35%, respectively). The peak normalized muscle forces in VAS, GMAX, and GMEDA increased by approximately 6, 9, and 19%, respectively, due to the stilts use. The peak normalized muscle force in GAS decreased by approximately 49%, while those in HAMS and GMEDP decreased by approximately 29 and 20%, respectively, due to the stilts use.

DISCUSSION AND CONCLUSION

Despite the hypothesis[20] that walking on the stilts may place workers at increased risk for musculoskeletal injuries, the musculoskeletal loadings during stilts walking have not been analyzed in the previous studies. In the current study, we estimated the joint moments and muscle forces during normal and stilts walking. In order to evaluate the effects of the stilts use on the musculoskeletal system, we compared the joint moments and musculoskeletal loadings for stilts walking with those for normal walking. Our calculations suggested that the use of stilts may potentially cause an increase of peak joint moments in the knee extension by approximately 25%, while induced slight reductions in peak joint moments of hip and ankle. The use of stilts was found to induce force re-distributions among the muscles. Our calculations indicated that, for the eight muscles groups analyzed, the forces in five muscle groups were increased, whereas those in three muscle groups were decreased due to the stilts use.

Quadriceps (which consists of vastus lateralis, vastus medialis, vastus intermedius, and rectus femoris) injuries are among the most common muscle injuries in sports[28] and also in some occupational activities.[26] Cross *et al.*[6] analyzed the MRIs of 25 patients with acute quadriceps muscle strains; they found that 60% of the quadriceps muscle strain injuries involve the rectus femoris. Our simulation results show that the loading levels in rectus femoris muscle increased substantially (180%) and slightly in vastus muscles (6%) due to the stilts use. However, the magnitudes of the muscle forces during the stilts walking are much lower than those that cause injuries.[28] Therefore, we cannot conclude whether the use of stilts would cause quadriceps injuries.

Clinical studies indicated that one of the most frequent thigh injuries was associated with hamstring strain.[3] The most hamstring injuries occur after in-direct trauma from excessive stretching or forceful contraction, leading to avulsion injuries or muscle strains and tears.[3] Our analysis indicated that the use of stilts would have little effect on the muscle loading in the hamstring (Fig. 7e).

The general trends and magnitudes of the joint moments for the normal walk obtained in our study agree well with those reported by Anderson and Pandy.[1] The differences in magnitude of the joint moments obtained in two different studies are likely due to the differences in subjects and the measurement errors of the motion capture system. The measured spatial displacements of the motion markers in the lateral direction contain relatively greater errors than those in the anterior/posterior and vertical directions, which may result in greater errors in the kinematics in the hip abduction and internal rotation and in ankle inversion.

For normal walking, the onsets and offsets of the predicted muscle forces agree well with the EMG measurements in literature.[23,25] Our results show that the time-history patterns of the muscle forces for stilts walk are similar to those for normal walk.

A comparison of the patterns of the joint moment in the sagittal plane during swing phase, i.e., hip extension, knee extension, and ankle dorsi flexion, indicates that the joint moments for the normal walking become zero immediately after the completion of the walk stance while those for the stilts walking oscillate for one cycle (Figs. 6b, 6d, and 6f). These oscillations of the joint moments are likely caused by the mass inertia effects of the stilts; and the legs have to apply extra force to stop the motion of the stilts at the late stance and during swing. The mass of a stilt is approximately equivalent to that of a thigh and twice that of a shank.[25] Since the mass in the thigh and shank is approximately evenly distributed in a cylindrical section with a length of about 0.4 m, whereas the mass in the stilt is unevenly distributed in a slim structure with a length of 1.02 m, the mass moments of inertia around the lateral axis of the stilt are estimated to reach around ten times those of the thigh and shank.

A comparison of the time-histories of the joint moment in hip extension (Fig. 6b) and knee extension (Fig. 6d) with those of muscle force in HAMS (Fig. 8e), GMAX (Fig. 8f), and RF (Fig. 8d) shows that the oscillations of the joint moments during the stilts walking in the swing phase are consistent with the increase in the muscle forces, indicating that the muscle force increases in RF and HAMS/GMAX reflect the muscles' efforts to initiate and stop the stilts oscillating during the stance-swing transition and terminal swing, respectively.

It is interesting to note that the peak of RF force occurs (Fig. 8d) around the peak hip flexion and knee extension moments (Fig. 6). Our calculations are consistent with the previous results that the min/max and other similar criteria predict peak forces of two-joint muscles when the muscle can contribute to both moments at the joints it crosses.[16,17] EMG data in literature are also consistent with this result.

The reduction of the peak ground reaction force in posterior direction (F_x) in early stance for stilts walking compared to that for normal walking (Fig. 4a) is because the subjects walked at a slower speed with stilts than they did without stilts. The phenomenon that at the middle stance the pattern of the ground reaction force in z-axis (F_z) for stilts walk is flatter than that for normal walk is likely due to the reduced ROM in the hip and knee joints. The reduced ROM in hip and knee joints during stilts walking would be comparable with the normal walking with shorter step length, which will result in a flatter pattern of the vertical ground reaction force. The effects of the reduced ROM for the stilts walking may also cause the reduced peak in F_x during loading response compared with the normal walking. The effects of reduced foot sensing of the ground contact with stilts and varied contact interactions between shoes/ground and stilts–foot–plate/ground may also be a contribution. The contact stiffness between the stilts–floor–plate and floor is higher than that between the shoes and floor. Besides, the foot is more sensitive to feel the contact conditions between foot and floor in normal walking than walking on stilts.

Stilts commonly used in constructions have an elevation from 0.3 to 1.0 m. In the present study, however, experimental studies and theoretical analysis have been performed using stilts with an elevation of 0.61 m. The height of the stilts will likely affect the musculoskeletal loadings during walking. The effects of the stilts height on the musculoskeletal loadings have yet to be studied.

In the current model, we assumed that the characteristics of the passive nonlinear-elastic behavior of the each muscle are identical. It is recognized that the passive elastic behaviors of the muscles do not play much role until the muscles are stretched beyond their optimum lengths. Since we calibrated the model to adapt the tendon lengths to the subject size before each simulation, such that the muscle length will possibly vary within its optimum range around the neutral position for each joint. Therefore, regardless of the possible inaccuracy of the passive-elastic data, the predicted muscle forces in our simulations are reasonable and the passive muscle forces do not seem to play a significant role.

A further limitation of our analysis is that the magnitudes of the predicted muscle forces cannot be directly validated to date. This is a current limitation for any multi-body dynamical simulations. Consequently, only the general trends and time sequences of the time-histories of the muscle forces predicted in the study are considered to be reliable. However, the joint moments and muscle forces for both stilts walking and normal walking were obtained using the same model parameters. The effects of the use of the stilts were analyzed by comparing the musculoskeletal loadings for stilts walking with those for normal walking. Therefore, the major conclusions of our study are little dependent on the variations in the model parameters and subjects.

In the current study, we have analyzed the joint moment and muscle forces in the lower extremities during stilts walking and theoretically evaluated the effects of the stilts use on the musculoskeletal loadings.

Our simulations suggested that the use of stilts may potentially cause an increase in loadings in five of eight major muscle groups in the lower extremities. Most remarkable was the force in RF muscle, which was found to increase 1.8 times for the stilts walking compared with that for the normal walking. The increases in muscle loading during the stilts walking may likely speed the muscle fatigue of the workers, influencing the postural balance and increasing the slip and fall risk. Our theoretical analysis is yet to be validated by further clinical and experimental studies.

APPENDIX A

The mass moment of inertia was determined by a swing test, as illustrated in Fig. A1. Assuming that the stilt has a mass of M and its center of mass is located at C (Fig. A1), the mass moment of inertia around Z-axis at C, I_{CZ}, is to be determined. Note that the local coordinates for the moments of inertia of stilts are determined for the convenience of the testing and they are different from the coordinate system of the human model. The stilt was hanged up using a thin string with negligible mass. At $t = 0$, the stilt was held at a small swing angle in $x-y$ plane; and it began to swing once it was released. The swing vibration of the stilt is governed by:

$$\ddot{\theta}_z + \omega_z^2 \theta_z = 0 \quad \text{(A1)}$$

where ω_z is the frequency of vibration and it is related to the mass moment of inertia, J_{oz}, by

$$\omega_z = \sqrt{\frac{Mgl}{J_{oz}}}, \quad J_{oz} = J_{CZ} + Ml^2. \quad \text{(A2)}$$

Once the vibration frequency, ω_z, is determined, the mass moment of inertia of the stilt, I_{CZ}, can be obtained by:

$$I_{CZ} = \frac{Mgl}{\omega_z^2} - Ml^2. \quad \text{(A3)}$$

In the test, the vibration frequency was estimated by measuring vibration period, T_z; so that $\omega_z = 2\pi/T_z$.

The mass moment of inertia around y-axis, J_{CY}, was determined using a similar approach by a swing test of the stilt in $x-z$ plane to determine the vibration frequency around y-axis. J_{CY} can then be evaluated by:

$$I_{CY} = \frac{Mgl}{\omega_y^2} - Ml^2 = \frac{MglT_y^2}{4\pi^2} - Ml^2. \quad \text{(A4)}$$

where ω_y and T_y are the vibration frequency and period around y-axis, respectively.

The mass moment of inertial around x-axis is estimated by:

$$I_{CX} \approx \frac{1}{2} MR^2 \quad \text{(A5)}$$

where R is the characteristic radius of the stilt.

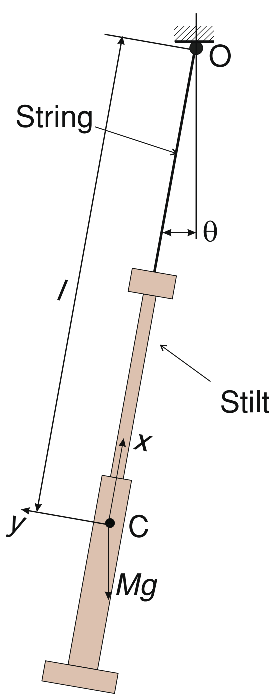

FIGURE A1. Test setup to determine the mass moment of inertia of stilt around *y*- and *z*-axis. The stilt with a mass of *M* was hung up via a thing string to a fixed point *O*. At *t* = 0, the stilt was held at a small angle, θ, from the plumb line and it was then released to swing freely in the *xy*-plane. The mass moment of inertia around *z*-axis, I_{CZ}, was determined in the tests by counting the swing frequency. The mass moment of inertia around *y*-axis, I_{CY}, was determined by a swing test in the *xz*-plane.

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DISCLAIMERS

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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